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Chapter 2

Fundamentals of the Mechanical Behavior of Materials

Questions

2.1 Can you calculate the percent elongation of materials based only on the information given in Fig. 2.6? Explain.

Recall that the percent elongation is defined by Eq. (2.6) on p. 33 and depends on the original gage length (l_o) of the specimen. From Fig. 2.6 on p. 37 only the necking strain (true and engineering) and true fracture strain can be determined. Thus, we cannot calculate the percent elongation of the specimen; also, note that the elongation is a function of gage length and increases with gage length.

2.2 Explain if it is possible for the curves in Fig. 2.4 to reach 0% elongation as the gage length is increased further.

The percent elongation of the specimen is a function of the initial and final gage lengths. When the specimen is being pulled, regardless of the original gage length, it will elongate uniformly (and permanently) until necking begins. Therefore, the specimen will always have a certain finite elongation. However, note that as the specimen's gage length is increased, the contribution of localized elongation (that is, necking) will decrease, but the total elongation will not approach zero.

2.3 Explain why the difference between engineering strain and true strain becomes larger as strain increases. Is this phenomenon true for both tensile and compressive strains? Explain.

The difference between the engineering and true strains becomes larger because of the way the strains are defined, respectively, as can be seen by inspecting Eqs. (2.1) on p. 30 and (2.9) on p. 35. This is true for both tensile and compressive strains.

2.4 Using the same scale for stress, we note that the tensile true-stress-true-strain curve is higher than the engineering stress-strain curve. Explain whether this condition also holds for a compression test.

During a compression test, the cross-sectional area of the specimen increases as the specimen height decreases (because of volume constancy) as the load is increased. Since true stress is defined as ratio of the load to the instantaneous cross-sectional area of the specimen, the true stress in compression will be lower than the engineering stress for a given load, assuming that friction between the platens and the specimen is negligible.

2.5 Which of the two tests, tension or compression, requires a higher capacity testing machine than the other? Explain.

The compression test requires a higher capacity machine because the cross-sectional area of the

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specimen increases during the test, which is the opposite of a tension test. The increase in area requires a load higher than that for the tension test to achieve the same stress level. Furthermore, note that compression-test specimens generally have a larger original cross-sectional area than those for tension tests, thus requiring higher forces.

2.6 Explain how the modulus of resilience of a material changes, if at all, as it is strained: (1) for an elastic, perfectly plastic material, and (2) for an elastic, linearly strain-hardening material.

2.7 If you pull and break a tension-test specimen rapidly, where would the temperature be the highest? Explain why.

Since temperature rise is due to the work input, the temperature will be highest in the necked region because that is where the strain, hence the energy dissipated per unit volume in plastic deformation, is highest.

2.8 Comment on the temperature distribution if the specimen in Question 2.7 is pulled very slowly.

If the specimen is pulled very slowly, the temperature generated will be dissipated throughout the specimen and to the environment. Thus, there will be no appreciable temperature rise anywhere, particularly with materials with high thermal conductivity.

2.9 In a tension test, the area under the true-stress-true-strain curve is the work done per unit volume (the specific work). We also know that the area under the load-elongation curve represents the work done on the specimen. If you divide this latter work by the volume of the specimen between the gage marks, you will determine the work done per unit volume (assuming that all deformation is confined between the gage marks). Will this specific work be the same as the area under the true-stress-true-strain curve? Explain. Will your answer be the same for any value of strain? Explain.

If we divide the work done by the total volume of the specimen between the gage lengths, we obtain the average specific work throughout the specimen. However, the area under the true stress-true strain curve represents the specific work done at the necked (and fractured) region in the specimen where the strain is a maximum. Thus, the answers will be different. However, up to the onset of necking (instability), the specific work calculated will be the same. This is because the strain is uniform throughout the specimen until necking begins.

2.10 The note at the bottom of Table 2.5 states that as temperature increases, C decreases and m increases. Explain why.

The value of C in Table 2.5 on p. 43 decreases with temperature because it is a measure of the strength of the material. The value of m increases with temperature because the material becomes more strain-rate sensitive, due to the fact that the higher the strain rate, the less time the material has to recover and recrystallize, hence its strength increases.

2.11 You are given the K and n values of two different materials. Is this information sufficient to determine which material is tougher? If not, what additional information do you need, and why?

Although the K and n values may give a good estimate of toughness, the true fracture stress and the true strain at fracture are required for accurate calculation of toughness. The modulus of elasticity and yield stress would provide information about the area under the elastic region; however, this region is very small and is thus usually negligible with respect to the rest of the stress-strain curve.

2.12 Modify the curves in Fig. 2.7 to indicate the effects of temperature. Explain the reasons for your changes.

These modifications can be made by lowering the slope of the elastic region and lowering the general height of the curves. See, for example, Fig. 2.10 on p. 42.

2.13 Using a specific example, show why the deformation rate, say in m/s, and the true strain rate are not the same.

The deformation rate is the quantity v in Eqs. (2.14), (2.15), (2.17), and (2.18) on pp. 41-46. Thus, when v is held constant during de-

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formation (hence a constant deformation rate), the true strain rate will vary, whereas the engineering strain rate will remain constant. Hence, the two quantities are not the same.

2.14 It has been stated that the higher the value of m, the more diffuse the neck is, and likewise, the lower the value of m, the more localized the neck is. Explain the reason for this behavior.

As discussed in Section 2.2.7 starting on p. 41, with high m values, the material stretches to a greater length before it fails; this behavior is an indication that necking is delayed with increasing m. When necking is about to begin, the necking region's strength with respect to the rest of the specimen increases, due to strain hardening. However, the strain rate in the necking region is also higher than in the rest of the specimen, because the material is elongating faster there. Since the material in the necked region becomes stronger as it is strained at a higher rate, the region exhibits a greater resistance to necking. The increase in resistance to necking thus depends on the magnitude of m. As the tension test progresses, necking becomes more *diffuse*, and the specimen becomes longer before fracture; hence, total elongation increases with increasing values of m (Fig. 2.13 on p. 45). As expected, the elongation after necking (*postuniform elongation*) also increases with increasing m. It has been observed that the value of m decreases with metals of increasing strength.

2.15 Explain why materials with high m values (such as hot glass and silly putty) when stretched slowly, undergo large elongations before failure. Consider events taking place in the necked region of the specimen.

The answer is similar to Answer 2.14 above.

2.16 Assume that you are running four-point bending tests on a number of identical specimens of the same length and cross-section, but with increasing distance between the upper points of loading (see Fig. 2.21b). What changes, if any, would you expect in the test results? Explain.

As the distance between the upper points of loading in Fig. 2.21b on p. 51 increases, the magnitude of the bending moment decreases. However, the volume of material subjected to the maximum bending moment (hence to maximum stress) increases. Thus, the probability of failure in the four-point test increases as this distance increases.

2.17 Would Eq. (2.10) hold true in the elastic range? Explain.

Note that this equation is based on volume constancy, i.e., $A_o l_o = Al$. We know, however, that because the Poisson's ratio ν is less than 0.5 in the elastic range, the volume is not constant in a tension test; see Eq. (2.47) on p. 69. Therefore, the expression is not valid in the elastic range.

2.18 Why have different types of hardness tests been developed? How would you measure the hardness of a very large object?

There are several basic reasons: (a) The overall hardness range of the materials; (b) the hardness of their constituents; see Chapter 3; (c) the thickness of the specimen, such as bulk versus foil; (d) the size of the specimen with respect to that of the indenter; and (e) the surface finish of the part being tested.

2.19 Which hardness tests and scales would you use for very thin strips of material, such as aluminum foil? Why?

Because aluminum foil is very thin, the indentations on the surface must be very small so as not to affect test results. Suitable tests would be a microhardness test such as Knoop or Vickers under very light loads (see Fig. 2.22 on p. 52). The accuracy of the test can be validated by observing any changes in the surface appearance opposite to the indented side.

2.20 List and explain the factors that you would consider in selecting an appropriate hardness test and scale for a particular application.

Hardness tests mainly have three differences:

(a) type of indenter,

(b) applied load, and

(c) method of indentation measurement (depth or surface area of indentation, or rebound of indenter).

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The hardness test selected would depend on the estimated hardness of the workpiece, its size and thickness, and if an average hardness or the hardness of individual microstructural components is desired. For instance, the scleroscope, which is portable, is capable of measuring the hardness of large pieces which otherwise would be difficult or impossible to measure by other techniques.

The Brinell hardness measurement leaves a fairly large indentation which provides a good measure of average hardness, while the Knoop test leaves a small indentation that allows, for example, the determination of the hardness of individual phases in a two-phase alloy, as well as inclusions. The small indentation of the Knoop test also allows it to be useful in measuring the hardness of very thin layers on parts, such as plating or coatings. Recall that the depth of indentation should be small relative to part thickness, and that any change on the bottom surface appearance makes the test results invalid.

2.21 In a Brinell hardness test, the resulting impression is found to be an ellipse. Give possible explanations for this phenomenon.

There are several possible reasons for this phenomenon, but the two most likely are anisotropy in the material and the presence of surface residual stresses in the material.

2.21 Referring to Fig. 2.22 on p. 52, note that the material for indenters are either steel, tungsten carbide, or diamond. Why isn't diamond used for all of the tests?

While diamond is the hardest material known, it would not, for example, be practical to make and use a 10-mm diamond indenter because the costs would be prohibitive. Consequently, a hard material such as those listed are sufficient for most hardness tests.

2.22 What effect, if any, does friction have in a hardness test? Explain.

The effect of friction has been found to be minimal. In a hardness test, most of the indentation occurs through plastic deformation, and there is very little sliding at the indenter-workpiece interface; see Fig. 2.25 on p. 55.

2.23 Describe the difference between creep and stress-relaxation phenomena, giving two examples for each as they relate to engineering applications.

Creep is the permanent deformation of a part that is under a load over a period of time, usually occurring at elevated temperatures. Stress relaxation is the decrease in the stress level in a part under a constant strain. Examples of creep include:

(a) turbine blades operating at high temperatures, and

(b) high-temperature steam linesand furnace components.

Stress relaxation is observed when, for example, a rubber band or a thermoplastic is pulled to a specific length and held at that length for a period of time. This phenomenon is commonly observed in rivets, bolts, and guy wires, as well as thermoplastic components.

2.24 Referring to the two impact tests shown in Fig. 2.31, explain how different the results would be if the specimens were impacted from the opposite directions.

Note that impacting the specimens shown in Fig. 2.31 on p. 60 from the opposite directions would subject the roots of the notches to compressive stresses, and thus they would not act as stress raisers. Thus, cracks would not propagate as they would when under tensile stresses. Consequently, the specimens would basically behave as if they were not notched.

2.25 If you remove layer *ad* from the part shown in Fig. 2.30d, such as by machining or grinding, which way will the specimen curve? (*Hint:* Assume that the part in diagram (d) can be modeled as consisting of four horizontal springs held at the ends. Thus, from the top down, we have compression, tension, compression, and tension springs.)

Since the internal forces will have to achieve a state of static equilibrium, the new part has to bow downward (i.e., it will hold water). Such residual-stress patterns can be modeled with a set of horizontal tension and compression

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springs. Note that the top layer of the material *ad* in Fig. 2.30d on p. 60, which is under compression, has the tendency to bend the bar upward. When this stress is relieved (such as by removing a layer), the bar will compensate for it by bending downward.

2.26 Is it possible to completely remove residual stresses in a piece of material by the technique described in Fig. 2.32 if the material is elastic, linearly strain hardening? Explain.

By following the sequence of events depicted in Fig. 2.32 on p. 61, it can be seen that it is not possible to completely remove the residual stresses. Note that for an elastic, linearly strain hardening material, σ'_c will never catch up with σ'_t.

2.27 Referring to Fig. 2.32, would it be possible to eliminate residual stresses by compression instead of tension? Assume that the piece of material will not buckle under the uniaxial compressive force.

Yes, by the same mechanism described in Fig. 2.32 on p. 61.

2.28 List and explain the desirable mechanical properties for the following: (1) elevator cable, (2) bandage, (3) shoe sole, (4) fish hook, (5) automotive piston, (6) boat propeller, (7) gas-turbine blade, and (8) staple.

The following are some basic considerations:

(a) Elevator cable: The cable should not elongate elastically to a large extent or undergo yielding as the load is increased. These requirements thus call for a material with a high elastic modulus and yield stress.

(b) Bandage: The bandage material must be compliant, that is, have a low stiffness, but have high strength in the membrane direction. Its inner surface must be permeable and outer surface resistant to environmental effects.

(c) Shoe sole: The sole should be compliant for comfort, with a high resilience. It should be tough so that it absorbs shock and should have high friction and wear resistance.

(d) Fish hook: A fish hook needs to have high strength so that it doesn't deform permanently under load, and thus maintain its shape. It should be stiff (for better control during its use) and should be resistant the environment it is used in (such as salt water).

(e) Automotive piston: This product must have high strength at elevated temperatures, high physical and thermal shock resistance, and low mass.

(f) Boat propeller: The material must be stiff (to maintain its shape) and resistant to corrosion, and also have abrasion resistance because the propeller encounters sand and other abrasive particles when operated close to shore.

(g) Gas turbine blade: A gas turbine blade operates at high temperatures (depending on its location in the turbine); thus it should have high-temperature strength and resistance to creep, as well as to oxidation and corrosion due to combustion products during its use.

(h) Staple: The properties should be closely parallel to that of a paper clip. The staple should have high ductility to allow it to be deformed without fracture, and also have low yield stress so that it can be bent (as well as unbent when removing it) easily without requiring excessive force.

2.29 Make a sketch showing the nature and distribution of the residual stresses in Figs. 2.31a and b before the parts were split (cut). Assume that the split parts are free from any stresses. (*Hint:* Force these parts back to the shape they were in before they were cut.)

As the question states, when we force back the split portions in the specimen in Fig. 2.31a on p. 60, we induce tensile stresses on the outer surfaces and compressive on the inner. Thus the original part would, along its total cross section, have a residual stress distribution of tension-compression-tension. Using the same technique, we find that the specimen in Fig. 2.31b would have a similar residual stress distribution prior to cutting.

2.30 It is possible to calculate the work of plastic deformation by measuring the temperature rise

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in a workpiece, assuming that there is no heat loss and that the temperature distribution is uniform throughout. If the specific heat of the material decreases with increasing temperature, will the work of deformation calculated using the specific heat at room temperature be higher or lower than the actual work done? Explain.

If we calculate the heat using a constant specific heat value in Eq. (2.65) on p. 73, the work will be higher than it actually is. This is because, by definition, as the specific heat decreases, less work is required to raise the workpiece temperature by one degree. Consequently, the calculated work will be higher than the actual work done.

2.31 Explain whether or not the volume of a metal specimen changes when the specimen is subjected to a state of (a) uniaxial compressive stress and (b) uniaxial tensile stress, all in the elastic range.

For case (a), the quantity in parentheses in Eq. (2.47) on p. 69 will be negative, because of the compressive stress. Since the rest of the terms are positive, the product of these terms is negative and, hence, there will be a decrease in volume (This can also be deduced intuitively.) For case (b), it will be noted that the volume will increase.

2.32 We know that it is relatively easy to subject a specimen to hydrostatic compression, such as by using a chamber filled with a liquid. Devise a means whereby the specimen (say, in the shape of a cube or a thin round disk) can be subjected to hydrostatic tension, or one approaching this state of stress. (Note that a thin-walled, internally pressurized spherical shell is not a correct answer, because it is subjected only to a state of plane stress.)

Two possible answers are the following:

(a) A solid cube made of a soft metal has all its six faces brazed to long square bars (of the same cross section as the specimen); the bars are made of a stronger metal. The six arms are then subjected to equal tension forces, thus subjecting the cube to equal tensile stresses.

(b) A thin, solid round disk (such as a coin) and made of a soft material is brazed between the ends of two solid round bars of the same diameter as that of the disk. When subjected to longitudinal tension, the disk will tend to shrink radially. But because it is thin and its flat surfaces are restrained by the two rods from moving, the disk will be subjected to tensile radial stresses. Thus, a state of triaxial (though not exactly hydrostatic) tension will exist within the thin disk.

2.33 Referring to Fig. 2.19, make sketches of the state of stress for an element in the reduced section of the tube when it is subjected to (1) torsion only, (2) torsion while the tube is internally pressurized, and (3) torsion while the tube is externally pressurized. Assume that the tube is closed end.

These states of stress can be represented simply by referring to the contents of this chapter as well as the relevant materials covered in texts on mechanics of solids.

2.34 A penny-shaped piece of soft metal is brazed to the ends of two flat, round steel rods of the same diameter as the piece. The assembly is then subjected to uniaxial tension. What is the state of stress to which the soft metal is subjected? Explain.

The penny-shaped soft metal piece will tend to contract radially due to the Poisson's ratio; however, the solid rods to which it attached will prevent this from happening. Consequently, the state of stress will tend to approach that of hydrostatic tension.

2.35 A circular disk of soft metal is being compressed between two flat, hardened circular steel punches having the same diameter as the disk. Assume that the disk material is perfectly plastic and that there is no friction or any temperature effects. Explain the change, if any, in the magnitude of the punch force as the disk is being compressed plastically to, say, a fraction of its original thickness.

Note that as it is compressed plastically, the disk will expand radially, because of volume constancy. An approximately donut-shaped

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material will then be pushed radially outward, which will then exert radial compressive stresses on the disk volume under the punches. The volume of material directly between the punches will now subjected to a triaxial compressive state of stress. According to yield criteria (see Section 2.11), the compressive stress exerted by the punches will thus increase, even though the material is not strain hardening. Therefore, the punch force will increase as deformation increases.

2.36 A perfectly plastic metal is yielding under the stress state σ_1, σ_2, σ_3, where $\sigma_1 > \sigma_2 > \sigma_3$. Explain what happens if σ_1 is increased.

Consider Fig. 2.36 on p. 67. Points in the interior of the yield locus are in an elastic state, whereas those on the yield locus are in a plastic state. Points outside the yield locus are not admissible. Therefore, an increase in σ_1 while the other stresses remain unchanged would require an increase in yield stress. This can also be deduced by inspecting either Eq. (2.36) or Eq. (2.37) on p. 64.

2.37 What is the dilatation of a material with a Poisson's ratio of 0.5? Is it possible for a material to have a Poisson's ratio of 0.7? Give a rationale for your answer.

It can be seen from Eq. (2.47) on p. 69 that the dilatation of a material with $\nu = 0.5$ is always zero, regardless of the stress state. To examine the case of $\nu = 0.7$, consider the situation where the stress state is hydrostatic tension. Equation (2.47) would then predict contraction under a tensile stress, a situation that cannot occur.

2.38 Can a material have a negative Poisson's ratio? Explain.

Solid material do not have a negative Poisson's ratio, with the exception of some composite materials (see Chapter 10), where there can be a negative Poisson's ratio in a given direction.

2.39 As clearly as possible, define plane stress and plane strain.

Plane stress is the situation where the stresses in one of the direction on an element are zero; plane strain is the situation where the strains in one of the direction are zero.

2.40 What test would you use to evaluate the hardness of a coating on a metal surface? Would it matter if the coating was harder or softer than the substrate? Explain.

The answer depends on whether the coating is relatively thin or thick. For a relatively thick coating, conventional hardness tests can be conducted, as long as the deformed region under the indenter is less than about one-tenth of the coating thickness. If the coating thickness is less than this threshold, then one must either rely on nontraditional hardness tests, or else use fairly complicated indentation models to extract the material behavior. As an example of the former, atomic force microscopes using diamond-tipped pyramids have been used to measure the hardness of coatings less than 100 nanometers thick. As an example of the latter, finite-element models of a coated substrate being indented by an indenter of a known geometry can be developed and then correlated to experiments.

2.41 List the advantages and limitations of the stress-strain relationships given in Fig. 2.7.

Several answers that are acceptable, and the student is encouraged to develop as many as possible. Two possible answers are: (1) there is a tradeoff between mathematical complexity and accuracy in modeling material behavior and (2) some materials may be better suited for certain constitutive laws than others.

2.42 Plot the data in Table 2.1 on a bar chart, showing the range of values, and comment on the results.

By the student. An example of a bar chart for the elastic modulus is shown below.

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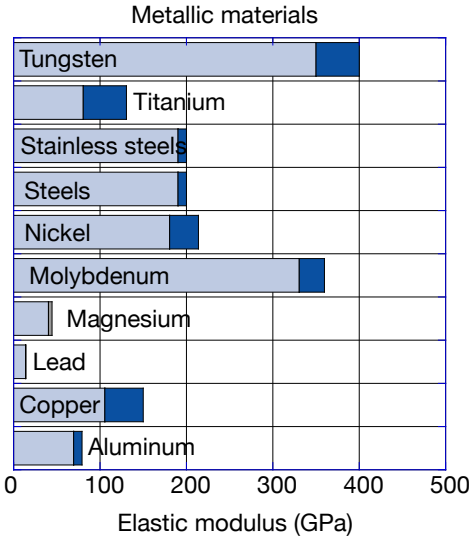

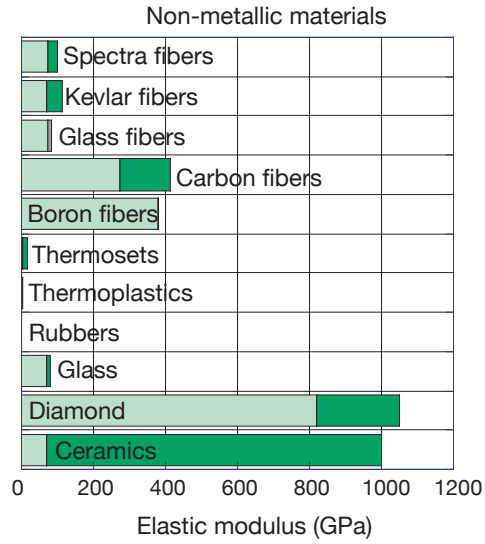

Typical comments regarding such a chart are:

(a) There is a smaller range for metals than for non-metals;

(b) Thermoplastics, thermosets and rubbers are orders of magnitude lower than metals and other non-metals;

(c) Diamond and ceramics can be superior to others, but ceramics have a large range of values.

2.43 A hardness test is conducted on as-received metal as a quality check. The results indicate that the hardness is too high, thus the material may not have sufficient ductility for the intended application. The supplier is reluctant to accept the return of the material, instead claiming that the diamond cone used in the Rockwell testing was worn and blunt, and hence the test needed to be recalibrated. Is this explanation plausible? Explain.

Refer to Fig. 2.22 on p. 52 and note that if an indenter is blunt, then the penetration, t, under a given load will be smaller than that using a sharp indenter. This then translates into a higher hardness. The explanation is plausible, but in practice, hardness tests are fairly reliable and measurements are consistent if the testing equipment is properly calibrated and routinely serviced.

2.44 Explain why a 0.2% offset is used to determine the yield strength in a tension test.

The value of 0.2% is somewhat arbitrary and is used to set some standard. A yield stress, representing the transition point from elastic to plastic deformation, is difficult to measure. This is because the stress-strain curve is not linearly proportional after the proportional limit, which can be as high as one-half the yield strength in some metals. Therefore, a transition from elastic to plastic behavior in a stress-strain curve is difficult to discern. The use of a 0.2% offset is a convenient way of consistently interpreting a yield point from stress-strain curves.

2.45 Referring to Question 2.44, would the offset method be necessary for a highly-strained-hardened material? Explain.

The 0.2% offset is still advisable whenever it can be used, because it is a standardized approach for determining yield stress, and thus one should not arbitrarily abandon standards. However, if the material is highly cold worked, there will be a more noticeable 'kink' in the stress-strain curve, and thus the yield stress is far more easily discernable than for the same material in the annealed condition.

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Problems

2.46 A strip of metal is originally 1.5 m long. It is stretched in three steps: first to a length of 1.75 m, then to 2.0 m, and finally to 3.0 m. Show that the total true strain is the sum of the true strains in each step, that is, that the strains are additive. Show that, using engineering strains, the strain for each step cannot be added to obtain the total strain.

The true strain is given by Eq. (2.9) on p. 35 as

$$\epsilon = \ln\left(\frac{l}{l_o}\right)$$

Therefore, the true strains for the three steps are:

$$\epsilon_1 = \ln\left(\frac{1.75}{1.5}\right) = 0.1541$$

$$\epsilon_2 = \ln\left(\frac{2.0}{1.75}\right) = 0.1335$$

$$\epsilon_3 = \ln\left(\frac{3.0}{2.0}\right) = 0.4055$$

The sum of these true strains is $\epsilon = 0.1541 + 0.1335 + 0.4055 = 0.6931$. The true strain from step 1 to 3 is

$$\epsilon = \ln\left(\frac{3}{1.5}\right) = 0.6931$$

Therefore the true strains are additive. Using the same approach for engineering strain as defined by Eq. (2.1), we obtain $e_1 = 0.1667$, $e_2 = 0.1429$, and $e_3 = 0.5$. The sum of these strains is $e_1 + e_2 + e_3 = 0.8096$. The engineering strain from step 1 to 3 is

$$e = \frac{l - l_o}{l_o} = \frac{3 - 1.5}{1.5} = \frac{1.5}{1.5} = 1$$

Note that this is not equal to the sum of the engineering strains for the individual steps.

2.47 A paper clip is made of wire 1.20-mm in diameter. If the original material from which the wire is made is a rod 15-mm in diameter, calculate the longitudinal and diametrical engineering and true strains that the wire has undergone.

Assuming volume constancy, we may write

$$\frac{l_f}{l_o} = \left(\frac{d_o}{d_f}\right)^2 = \left(\frac{15}{1.20}\right)^2 = 156.25 \approx 156$$

Letting l_0 be unity, the longitudinal engineering strain is $e_1 = (156 - 1)/1 = 155$. The diametral engineering strain is calculated as

$$e_d = \frac{1.2 - 15}{15} = -0.92$$

The longitudinal true strain is given by Eq. (2.9) on p. 35 as

$$\epsilon = \ln\left(\frac{l}{l_o}\right) = \ln(155) = 5.043$$

The diametral true strain is

$$\epsilon_d = \ln\left(\frac{1.20}{15}\right) = -2.526$$

Note the large difference between the engineering and true strains, even though both describe the same phenomenon. Note also that the sum of the true strains (recognizing that the radial strain is $\epsilon_r = \ln\left(\frac{0.60}{7.5}\right) = -2.526$) in the three principal directions is zero, indicating volume constancy in plastic deformation.

2.48 A material has the following properties: UTS = 50,000 psi and $n = 0.25$ Calculate its strength coefficient K.

Let us first note that the true UTS of this material is given by $\text{UTS}_{\text{true}} = Kn^n$ (because at necking $\epsilon = n$). We can then determine the value of this stress from the UTS by following a procedure similar to Example 2.1. Since $n = 0.25$, we can write

$$\begin{aligned}\text{UTS}_{\text{true}} &= \text{UTS}\left(\frac{A_o}{A_{\text{neck}}}\right) = \text{UTS}\left(e^{0.25}\right) \\ &= (50,000)(1.28) = 64,200 \text{ psi}\end{aligned}$$

Therefore, since $\text{UTS}_{\text{true}} = Kn^n$,

$$K = \frac{\text{UTS}_{\text{true}}}{n^n} = \frac{64,200}{0.25^{0.25}} = 90,800 \text{ psi}$$

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2.49 Based on the information given in Fig. 2.6, calculate the ultimate tensile strength of annealed 70-30 brass.

From Fig. 2.6 on p. 37, the true stress for annealed 70-30 brass at necking (where the slope becomes constant; see Fig. 2.7a on p. 40) is found to be about 60,000 psi, while the true strain is about 0.2. We also know that the ratio of the original to necked areas of the specimen is given by

$$\ln\left(\frac{A_o}{A_{\text{neck}}}\right) = 0.20$$

or

$$\frac{A_{\text{neck}}}{A_o} = e^{-0.20} = 0.819$$

Thus,

$$\text{UTS} = (60,000)(0.819) = 49,100 \text{ psi}$$

2.50 Calculate the ultimate tensile strength (engineering) of a material whose strength coefficient is 400 MPa and of a tensile-test specimen that necks at a true strain of 0.20.

In this problem we have $K = 400$ MPa and $n = 0.20$. Following the same procedure as in Example 2.1, we find the true ultimate tensile strength is

$$\sigma = (400)(0.20)^{0.20} = 290 \text{ MPa}$$

and

$$A_{\text{neck}} = A_o e^{-0.20} = 0.81 A_o$$

Consequently,

$$\text{UTS} = (290)(0.81) = 237 \text{ MPa}$$

2.51 A cable is made of four parallel strands of different materials, all behaving according to the equation $\sigma = K\epsilon^n$, where $n = 0.3$ The materials, strength coefficients, and cross sections are as follows:

Material A: $K = 450$ MPa, $A_o = 7$ mm^2;
Material B: $K = 600$ MPa, $A_o = 2.5$ mm^2;
Material C: $K = 300$ MPa, $A_o = 3$ mm^2;
Material D: $K = 760$ MPa, $A_o = 2$ mm^2;

(a) Calculate the maximum tensile load that this cable can withstand prior to necking.

(b) Explain how you would arrive at an answer if the n values of the three strands were different from each other.

(a) Necking will occur when $\epsilon = n = 0.3$. At this point the true stresses in each cable are (from $\sigma = K\epsilon^n$), respectively,

$$\sigma_A = (450)0.3^{0.3} = 314 \text{ MPa}$$
$$\sigma_B = (600)0.3^{0.3} = 418 \text{ MPa}$$
$$\sigma_C = (300)0.3^{0.3} = 209 \text{ MPa}$$
$$\sigma_D = (760)0.3^{0.3} = 530 \text{ MPa}$$

The areas at necking are calculated as follows (from $A_{\text{neck}} = A_o e^{-n}$):

$$A_A = (7)e^{-0.3} = 5.18 \text{ mm}^2$$
$$A_B = (2.5)e^{-0.3} = 1.85 \text{ mm}^2$$
$$A_C = (3)e^{-0.3} = 2.22 \text{ mm}^2$$
$$A_D = (2)e^{-0.3} = 1.48 \text{ mm}^2$$

Hence the total load that the cable can support is

$$\begin{aligned} P &= (314)(5.18) + (418)(1.85) \\ &\quad +(209)(2.22) + (530)(1.48) \\ &= 3650 \text{ N} \end{aligned}$$

(b) If the n values of the four strands were different, the procedure would consist of plotting the load-elongation curves of the four strands on the same chart, then obtaining graphically the maximum load. Alternately, a computer program can be written to determine the maximum load.

2.52 Using only Fig. 2.6, calculate the maximum load in tension testing of a 304 stainless-steel round specimen with an original diameter of 0.5 in.

We observe from Fig. 2.6 on p. 37 that necking begins at a true strain of about 0.1, and that the true UTS is about 110,000 psi. The original cross-sectional area is $A_o = \pi(0.25 \text{ in})^2 = 0.196 \text{ in}^2$. Since $n = 0.1$, we follow a procedure similar to Example 2.1 and show that

$$\frac{A_o}{A_{\text{neck}}} = e^{0.1} = 1.1$$

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Thus

$$\text{UTS} = \frac{110,000}{1.1} = 100,000 \text{ psi}$$

Hence the maximum load is

$$F = (\text{UTS})(A_o) = (100,000)(0.196)$$

or $F = 19,600$ lb.

2.53 Using the data given in Table 2.1, calculate the values of the shear modulus G for the metals listed in the table.

The important equation is Eq. (2.24) on p. 49 which gives the shear modulus as

$$G = \frac{E}{2(1+\nu)}$$

The following values can be calculated (mid-range values of ν are taken as appropriate):

Material	E (GPa)	ν	G (GPa)
Al & alloys	69-79	0.32	26-30
Cu & alloys	105-150	0.34	39-56
Pb & alloys	14	0.43	4.9
Mg & alloys	41-45	0.32	15.5-17.0
Mo & alloys	330-360	0.32	125-136
Ni & alloys	180-214	0.31	69-82
Steels	190-200	0.30	73-77
Stainless steels	190-200	0.29	74-77
Ti & alloys	80-130	0.32	30-49
W & alloys	350-400	0.27	138-157
Ceramics	70-1000	0.2	29-417
Glass	70-80	0.24	28-32
Rubbers	0.01-0.1	0.5	0.0033-0.033
Thermoplastics	1.4-3.4	0.36	0.51-1.25
Thermosets	3.5-17	0.34	1.3-6.34

2.54 Derive an expression for the toughness of a material whose behavior is represented by the equation $\sigma = K(\epsilon + 0.2)^n$ and whose fracture strain is denoted as ϵ_f.

Recall that toughness is the area under the stress-strain curve, hence the toughness for this material would be given by

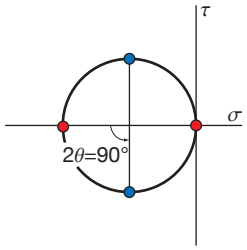
$$\begin{aligned}\text{Toughness} &= \int_0^{\epsilon_f} \sigma \, d\epsilon \\ &= \int_0^{\epsilon_f} K(\epsilon + 0.2)^n \, d\epsilon \\ &= \frac{K}{n+1}\left[(\epsilon_f + 0.2)^{n+1} - 0.2^{n+1}\right]\end{aligned}$$

2.55 A cylindrical specimen made of a brittle material 1 in. high and with a diameter of 1 in. is subjected to a compressive force along its axis. It is found that fracture takes place at an angle of 45° under a load of 30,000 lb. Calculate the shear stress and the normal stress acting on the fracture surface.

Assuming that compression takes place without friction, note that two of the principal stresses will be zero. The third principal stress acting on this specimen is normal to the specimen and its magnitude is

$$\sigma_3 = \frac{30,000}{\pi(0.5)^2} = 38,200 \text{ psi}$$

The Mohr's circle for this situation is shown below.



The fracture plane is oriented at an angle of 45°, corresponding to a rotation of 90° on the Mohr's circle. This corresponds to a stress state on the fracture plane of $\sigma = -19,100$ psi and $\tau = 19,100$ psi.

2.56 What is the modulus of resilience of a highly cold-worked piece of steel with a hardness of 300 HB? Of a piece of highly cold-worked copper with a hardness of 150 HB?

Referring to Fig. 2.24 on p. 55, the value of c in Eq. (2.29) on p. 54 is approximately 3.2 for highly cold-worked steels and around 3.4 for cold-worked aluminum. Therefore, we can approximate $c = 3.3$ for cold-worked copper. However, since the Brinell hardness is in units of kg/mm^2, from Eq. (2.29) we can write

$$T_{\text{steel}} = \frac{H}{3.2} = \frac{300}{3.2} = 93.75 \text{ kg/mm}^2 = 133 \text{ ksi}$$

$$T_{\text{Cu}} = \frac{H}{3.3} = \frac{150}{3.3} = 45.5 \text{ kg/mm}^2 = 64.6 \text{ ksi}$$

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From Table 2.1, $E_{\text{steel}} = 30 \times 10^6$ psi and $E_{\text{Cu}} = 15 \times 10^6$ psi. The modulus of resilience is calculated from Eq. (2.5). For steel:

$$\text{Modulus of Resilience} = \frac{Y^2}{2E} = \frac{(133,000)^2}{2(30 \times 10^6)}$$

or a modulus of resilience for steel of 295 in-lb/in^3. For copper,

$$\text{Modulus of Resilience} = \frac{Y^2}{2E} = \frac{(62,200)^2}{2(15 \times 10^6)}$$

or a modulus of resilience for copper of 129 in-lb/in^3.

Note that these values are slightly different than the values given in the text; this is due to the fact that (a) highly cold-worked metals such as these have a much higher yield stress than the annealed materials described in the text, and (b) arbitrary property values are given in the statement of the problem.

2.57 Calculate the work done in frictionless compression of a solid cylinder 40 mm high and 15 mm in diameter to a reduction in height of 75% for the following materials: (1) 1100-O aluminum, (2) annealed copper, (3) annealed 304 stainless steel, and (4) 70-30 brass, annealed.

The work done is calculated from Eq. (2.62) on p. 71 where the specific energy, u, is obtained from Eq. (2.60). Since the reduction in height is 75%, the final height is 10 mm and the absolute value of the true strain is

$$\epsilon = \ln\left(\frac{40}{10}\right) = 1.386$$

K and n are obtained from Table 2.3 as follows:

Material	K (MPa)	n
1100-O Al	180	0.20
Cu, annealed	315	0.54
304 Stainless, annealed	1300	0.30
70-30 brass, annealed	895	0.49

The u values are then calculated from Eq. (2.60). For example, for 1100-O aluminum, where K is 180 MPa and n is 0.20, u is calculated as

$$u = \frac{K\epsilon^{n+1}}{n+1} = \frac{(180)(1.386)^{1.2}}{1.2} = 222 \text{ MN/m}^3$$

The volume is calculated as $V = \pi r^2 l = \pi(0.0075)^2(0.04) = 7.069 \times 10^{-6}$ m^3. The work done is the product of the specific work, u, and the volume, V. Therefore, the results can be tabulated as follows.

Material	u (MN/m^3)	Work (Nm)
1100-O Al	222	1562
Cu, annealed	338	2391
304 Stainless, annealed	1529	10,808
70-30 brass, annealed	977	6908

2.58 A material has a strength coefficient $K = 100,000$ psi Assuming that a tensile-test specimen made from this material begins to neck at a true strain of 0.17, show that the ultimate tensile strength of this material is 62,400 psi.

The approach is the same as in Example 2.1. Since the necking strain corresponds to the maximum load and the necking strain for this material is given as $\epsilon = n = 0.17$, we have, as the true ultimate tensile strength:

$$\text{UTS}_{\text{true}} = (100,000)(0.17)^{0.17} = 74,000 \text{ psi.}$$

The cross-sectional area at the onset of necking is obtained from

$$\ln\left(\frac{A_o}{A_{\text{neck}}}\right) = n = 0.17.$$

Consequently,

$$A_{\text{neck}} = A_o e^{-0.17}$$

and the maximum load, P, is

$$\begin{aligned} P &= \sigma A = (\text{UTS}_{\text{true}})A_o e^{-0.17} \\ &= (74,000)(0.844)(A_o) = 62,400A_o \text{ lb.} \end{aligned}$$

Since UTS$= P/A_o$, we have UTS = 62,400 psi.

2.59 A tensile-test specimen is made of a material represented by the equation $\sigma = K(\epsilon + n)^n$. (a) Determine the true strain at which necking will begin. (b) Show that it is possible for an engineering material to exhibit this behavior.

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(a) In Section 2.2.4 on p. 38 we noted that instability, hence necking, requires the following condition to be fulfilled:

$$\frac{d\sigma}{d\epsilon} = \sigma$$

Consequently, for this material we have

$$Kn\left(\epsilon + n\right)^{n-1} = K\left(\epsilon + n\right)^{n}$$

This is solved as $n = 0$; thus necking begins as soon as the specimen is subjected to tension.

(b) Yes, this behavior is possible. Consider a tension-test specimen that has been strained to necking and then unloaded. Upon loading it again in tension, it will immediately begin to neck.

2.60 Take two solid cylindrical specimens of equal diameter but different heights. Assume that both specimens are compressed (frictionless) by the same percent reduction, say 50%. Prove that the final diameters will be the same.

Let's identify the shorter cylindrical specimen with the subscript s and the taller one as t, and their original diameter as D. Subscripts f and o indicate final and original, respectively. Because both specimens undergo the same percent reduction in height, we can write

$$\frac{h_{tf}}{h_{to}} = \frac{h_{sf}}{h_{so}}$$

and from volume constancy,

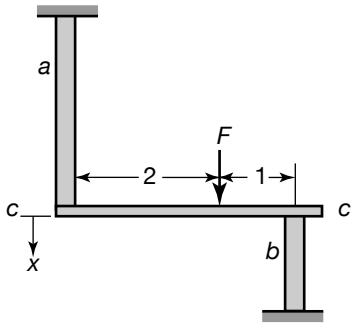
$$\frac{h_{tf}}{h_{to}} = \left(\frac{D_{to}}{D_{tf}}\right)^2$$

and

$$\frac{h_{sf}}{h_{so}} = \left(\frac{D_{so}}{D_{sf}}\right)^2$$

Because $D_{to} = D_{so}$, we note from these relationships that $D_{tf} = D_{sf}$.

2.61 A horizontal rigid bar c-c is subjecting specimen a to tension and specimen b to frictionless compression such that the bar remains horizontal. (See the accompanying figure.) The force F is located at a distance ratio of 2:1. Both specimens have an original cross-sectional area of 1 in^2 and the original lengths are $a = 8$ in. and $b = 4.5$ in. The material for specimen a has a true-stress-true-strain curve of $\sigma = 100,000\epsilon^{0.5}$. Plot the true-stress-true-strain curve that the material for specimen b should have for the bar to remain horizontal during the experiment.



From the equilibrium of vertical forces and to keep the bar horizontal, we note that $2F_a = F_b$. Hence, in terms of true stresses and instantaneous areas, we have

$$2\sigma_a A_a = \sigma_b A_b$$

From volume constancy we also have, in terms of original and final dimensions

$$A_{oa}L_{oa} = A_a L_a$$

and

$$A_{ob}L_{ob} = A_b L_b$$

where $L_{oa} = (8/4.5)L_{ob} = 1.78L_{ob}$. From these relationships we can show that

$$\sigma_b = 2\left(\frac{8}{4.5}\right)K\sigma_a\left(\frac{L_b}{L_a}\right)$$

Since $\sigma_a = K\epsilon_a^{0.5}$ where $K = 100,000$ psi, we can now write

$$\sigma_b = \left(\frac{16K}{4.5}\right)\left(\frac{L_b}{L_a}\right)\sqrt{\epsilon_a}$$

Hence, for a deflection of x,

$$\sigma_b = \left(\frac{16K}{4.5}\right)\left(\frac{4.5 - x}{8 + x}\right)\sqrt{\ln\left(\frac{8 + x}{8}\right)}$$

The true strain in specimen b is given by

$$\epsilon_b = \ln\left(\frac{4.5 - x}{4.5}\right)$$

By inspecting the figure in the problem statement, we note that while specimen a gets

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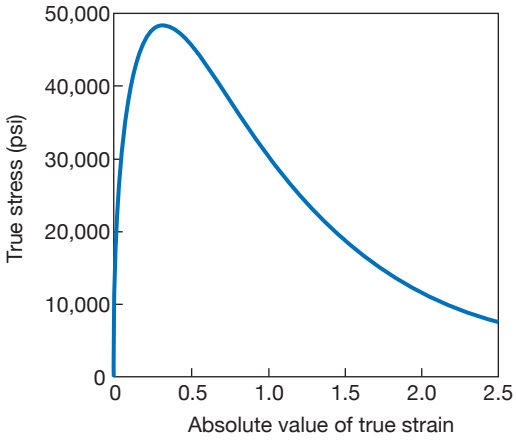
longer, it will continue exerting some force F_a. However, specimen b will eventually acquire a cross-sectional area that will become infinite as x approaches 4.5 in., thus its strength must approach zero. This observation suggests that specimen b cannot have a true stress-true strain curve typical of metals, and that it will have a maximum at some strain. This is seen in the plot of σ_b shown below.



2.62 Inspect the curve that you obtained in Problem 2.61. Does a typical strain-hardening material behave in that manner? Explain.

Based on the discussions in Section 2.2.3 starting on p. 35, it is obvious that ordinary metals would not normally behave in this manner. However, under certain conditions, the following could explain such behavior:

- When specimen b is heated to higher and higher temperatures as deformation progresses, with its strength decreasing as x is increased further after the maximum value of stress.
- In compression testing of brittle materials, such as ceramics, when the specimen begins to fracture.
- If the material is susceptible to thermal softening, then it can display such behavior with a sufficiently high strain rate.

2.63 In a disk test performed on a specimen 40-mm in diameter and 5 m thick, the specimen fractures at a stress of 500 MPa. What was the load on the disk at fracture?

Equation (2.20) is used to solve this problem. Noting that $\sigma = 500$ MPa, $d = 40$ mm $= 0.04$ m, and $t = 5$ mm $= 0.005$ m, we can write

$$\sigma = \frac{2P}{\pi dt} \quad \rightarrow \quad P = \frac{\sigma \pi dt}{2}$$

Therefore

$$P = \frac{(500 \times 10^6)\pi(0.04)(0.005)}{2} = 157 \text{ kN}.$$

2.64 In Fig. 2.32a, let the tensile and compressive residual stresses both be 10,000 psi and the modulus of elasticity of the material be 30×10^6 psi, with a modulus of resilience of 30 in.-lb/in^3. If the original length in diagram (a) is 20 in., what should be the stretched length in diagram (b) so that, when unloaded, the strip will be free of residual stresses?

Note that the yield stress can be obtained from Eq. (2.5) on p. 31 as

$$\text{Mod. of Resilience} = \text{MR} = \frac{Y^2}{2E}$$

Thus,

$$Y = \sqrt{2(\text{MR})E} = \sqrt{2(30)(30 \times 10^6)}$$

or $Y = 42,430$ psi. Using Eq. (2.32), the strain required to relieve the residual stress is:

$$\epsilon = \frac{\sigma_c}{E} + \frac{Y}{E} = \frac{10,000}{30 \times 10^6} + \frac{42,430}{30 \times 10^6} = 0.00175$$

Therefore,

$$\epsilon = \ln\left(\frac{l_f}{l_o}\right) = \ln\left(\frac{l_f}{20 \text{ in.}}\right) = 0.00175$$

Therefore, $l_f = 20.035$ in.

2.65 Show that you can take a bent bar made of an elastic, perfectly plastic material and straighten it by stretching it into the plastic range. (*Hint:* Observe the events shown in Fig. 2.32.)

The series of events that takes place in straightening a bent bar by stretching it can be visualized by starting with a stress distribution as in Fig. 2.32a on p. 61, which would represent the unbending of a bent section. As we apply tension, we algebraically add a uniform tensile stress to this stress distribution. Note that the change in the stresses is the same as that depicted in Fig. 2.32d, namely, the tensile stress

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increases and reaches the yield stress, Y. The compressive stress is first reduced in magnitude, then becomes tensile. Eventually, the whole cross section reaches the constant yield stress, Y. Because we now have a uniform stress distribution throughout its thickness, the bar becomes straight and remains straight upon unloading.

2.66 A bar 1 m long is bent and then stress relieved. The radius of curvature to the neutral axis is 0.50 m. The bar is 30 mm thick and is made of an elastic, perfectly plastic material with $Y = 600$ MPa and $E = 200$ GPa. Calculate the length to which this bar should be stretched so that, after unloading, it will become and remain straight.

When the curved bar becomes straight, the engineering strain it undergoes is given by the expression

$$e = \frac{t}{2\rho}$$

where t is the thickness and ρ is the radius to the neutral axis. Hence in this case,

$$e = \frac{(0.030)}{2(0.50)} = 0.03$$

Since $Y = 600$ MPa and $E = 200$ GPa, we find that the elastic limit for this material is at an elastic strain of

$$e = \frac{Y}{E} = \frac{600 \text{ MPa}}{200 \text{ GPa}} = 0.003$$

which is much smaller than 0.05. Following the description in Answer 2.65 above, we find that the strain required to straighten the bar is

$$e = (2)(0.003) = 0.006$$

or

$$\frac{l_f - l_o}{l_o} = 0.006 \quad \rightarrow \quad l_f = 0.006 l_o + l_o$$

or $l_f = 1.006$ m.

2.67 Assume that a material with a uniaxial yield stress Y yields under a stress state of principal stresses σ_1, σ_2, σ_3, where $\sigma_1 > \sigma_2 > \sigma_3$. Show that the superposition of a hydrostatic stress, p, on this system (such as placing the specimen in a chamber pressurized with a liquid) does not affect yielding. In other words, the material will still yield according to yield criteria.

Let's consider the distortion-energy criterion, although the same derivation could be performed with the maximum shear stress criterion as well. Equation (2.37) on p. 64 gives

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$$

Now consider a new stress state where the principal stresses are

$$\sigma_1' = \sigma_1 + p$$

$$\sigma_2' = \sigma_2 + p$$

$$\sigma_3' = \sigma_3 + p$$

which represents a new loading with an additional hydrostatic pressure, p. The distortion-energy criterion for this stress state is

$$(\sigma_1' - \sigma_2')^2 + (\sigma_2' - \sigma_3')^2 + (\sigma_3' - \sigma_1')^2 = 2Y^2$$

or

$$\begin{aligned} 2Y^2 \quad = \quad & [(\sigma_1 + p) - (\sigma_2 + p)]^2 \\ & + [(\sigma_2 + p) - (\sigma_3 + p)]^2 \\ & + [(\sigma_3 + p) - (\sigma_1 + p)]^2 \end{aligned}$$

which can be simplified as

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$$

which is the original yield criterion. Hence, the yield criterion is unaffected by the superposition of a hydrostatic pressure.

2.68 Give two different and specific examples in which the maximum-shear-stress and the distortion-energy criteria give the same answer.

In order to obtain the same answer for the two yield criteria, we refer to Fig. 2.36 on p. 67 for plane stress and note the coordinates at which the two diagrams meet. Examples are: simple tension, simple compression, equal biaxial tension, and equal biaxial compression. Thus, acceptable answers would include (a) wire rope, as used on a crane to lift loads; (b) spherical pressure vessels, including balloons and gas storage tanks, and (c) shrink fits.

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2.69 A thin-walled spherical shell with a yield stress Y is subjected to an internal pressure p. With appropriate equations, show whether or not the pressure required to yield this shell depends on the particular yield criterion used.

Here we have a state of plane stress with equal biaxial tension. The answer to Problem 2.68 leads one to immediately conclude that both the maximum shear stress and distortion energy criteria will give the same results. We will now demonstrate this more rigorously. The principal membrane stresses are given by

$$\sigma_1 = \sigma_2 = \frac{pr}{2t}$$

and

$$\sigma_3 = 0$$

Using the maximum shear-stress criterion, we find that

$$\sigma_1 - 0 = Y$$

hence

$$p = \frac{2tY}{r}$$

Using the distortion-energy criterion, we have

$$(0-0)^2 + (\sigma_2 - 0)^2 + (0 - \sigma_1)^2 = 2Y^2$$

Since $\sigma_1 = \sigma_2$, then this gives $\sigma_1 = \sigma_2 = Y$, and the same expression is obtained for pressure.

2.70 Show that, according to the distortion-energy criterion, the yield stress in plane strain is $1.15Y$ where Y is the uniaxial yield stress of the material.

A plane-strain condition is shown in Fig. 2.35d on p. 67, where σ_1 is the yield stress of the material in plane strain (Y'), σ_3 is zero, and $\epsilon_2 = 0$. From Eq. 2.43b on p. 68, we find that $\sigma_2 = \sigma_1/2$. Substituting these into the distortion-energy criterion given by Eq. (2.37) on p.64,

$$\left(\sigma_1 - \frac{\sigma_1}{2}\right)^2 + \left(\frac{\sigma_1}{2} - 0\right)^2 + (0 - \sigma_1)^2 = 2Y^2$$

and

$$\frac{3\sigma_1^2}{2} = 2Y^2$$

hence

$$\sigma_1 = \frac{2}{\sqrt{3}}Y \approx 1.15Y$$

2.71 What would be the answer to Problem 2.70 if the maximum-shear-stress criterion were used?

Because σ_2 is an intermediate stress and using Eq. (2.36), the answer would be

$$\sigma_1 - 0 = Y$$

hence the yield stress in plane strain will be equal to the uniaxial yield stress, Y.

2.72 A closed-end, thin-walled cylinder of original length l, thickness t, and internal radius r is subjected to an internal pressure p. Using the generalized Hooke's law equations, show the change, if any, that occurs in the length of this cylinder when it is pressurized. Let $\nu = 0.33$.

A closed-end, thin-walled cylinder under internal pressure is subjected to the following principal stresses:

$$\sigma_1 = \frac{pr}{2t}; \qquad \sigma_2 = \frac{pr}{t}; \quad \sigma_3 = 0$$

where the subscript 1 is the longitudinal direction, 2 is the hoop direction, and 3 is the thickness direction. From Hooke's law given by Eq. (2.33) on p. 63,

$$\begin{aligned}\epsilon_1 &= \frac{1}{E}\left[\sigma_1 - \nu\left(\sigma_2 + \sigma_3\right)\right] \\ &= \frac{1}{E}\left[\frac{pr}{2t} - \frac{1}{3}\left(\frac{pr}{t} + 0\right)\right] \\ &= \frac{pr}{6tE}\end{aligned}$$

Since all the quantities are positive (note that in order to produce a tensile membrane stress, the pressure is positive as well), the longitudinal strain is finite and positive. Thus the cylinder becomes longer when pressurized, as it can also be deduced intuitively.

2.73 A round, thin-walled tube is subjected to tension in the elastic range. Show that both the thickness and the diameter of the tube decrease as tension increases.

The stress state in this case is σ_1, $\sigma_2 = \sigma_3 = 0$. From the generalized Hooke's law equations given by Eq. (2.33) on p. 63, and denoting the axial direction as 1, the hoop direction as 2, and the radial direction as 3, we have for the hoop strain:

$$\epsilon_2 = \frac{1}{E}\left[\sigma_2 - \nu\left(\sigma_1 + \sigma_3\right)\right] = -\frac{\nu\sigma_1}{E}$$

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Therefore, the diameter is negative for a tensile (positive) value of σ_1. For the radial strain, the generalized Hooke's law gives

$$\epsilon_3 = \frac{1}{E}\left[\sigma_3 - \nu\left(\sigma_1 + \sigma_2\right)\right] = -\frac{\nu\sigma_1}{E}$$

Therefore, the radial strain is also negative and the wall becomes thinner for a positive value of σ_1.

2.74 Take a long cylindrical balloon and, with a thin felt-tip pen, mark a small square on it. What will be the shape of this square after you blow up the balloon: (1) a larger square, (2) a rectangle, with its long axis in the circumferential directions, (3) a rectangle, with its long axis in the longitudinal direction, or (4) an ellipse? Perform this experiment and, based on your observations, explain the results, using appropriate equations. Assume that the material the balloon is made of is perfectly elastic and isotropic, and that this situation represents a thin-walled closed-end cylinder under internal pressure.

This is a simple graphic way of illustrating the generalized Hooke's law equations. A balloon is a readily available and economical method of demonstrating these stress states. It is also encouraged to assign the students the task of predicting the shape numerically; an example of a valuable experiment involves partially inflating the balloon, drawing the square, then expanding it further and having the students predict the dimensions of the square.

Although not as readily available, a rubber tube can be used to demonstrate the effects of torsion in a similar manner.

2.75 Take a cubic piece of metal with a side length l_o and deform it plastically to the shape of a rectangular parallelepiped of dimensions l_1, l_2, and l_3. Assuming that the material is rigid and perfectly plastic, show that volume constancy requires that the following expression be satisfied: $\epsilon_1 + \epsilon_2 + \epsilon_3 = 0$.

The initial volume and the final volume are constant, so that

$$l_o l_o l_o = l_1 l_2 l_3 \quad \rightarrow \quad \frac{l_1 l_2 l_3}{l_o l_o l_o} = 1$$

Taking the natural log of both sides,

$$\ln\left(\frac{l_1 l_2 l_3}{l_o l_o l_o}\right) = \ln(1) = 0$$

since $\ln(AB) = \ln(A) + \ln(B)$,

$$\ln\left(\frac{l_1}{l_o}\right) + \ln\left(\frac{l_2}{l_o}\right) + \ln\left(\frac{l_3}{l_o}\right) = 0$$

From the definition of true strain given by Eq. (2.9) on p. 35, $\ln\left(\frac{l_1}{l_0}\right) = \epsilon_1$, etc., so that

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0.$$

2.76 What is the diameter of an originally 30-mm-diameter solid steel ball when it is subjected to a hydrostatic pressure of 5 GPa?

From Eq. (2.46) on p. 68 and noting that, for this case, all three strains are equal and all three stresses are equal in magnitude,

$$3\epsilon = \left(\frac{1-2\nu}{E}\right)(-3p)$$

where p is the hydrostatic pressure. Thus, from Table 2.1 on p. 32 we take values for steel of $\nu = 0.3$ and $E = 200$ GPa, so that

$$\epsilon = \left(\frac{1-2\nu}{E}\right)(-p) = \left(\frac{1-0.6}{200}\right)(-5)$$

or $\epsilon = -0.01$. Therefore

$$\ln\left(\frac{D_f}{D_o}\right) = -0.01$$

Solving for D_f,

$$D_f = D_o e^{-0.01} = (20)e^{-0.01} = 19.8 \text{ mm}$$

2.77 Determine the effective stress and effective strain in plane-strain compression according to the distortion-energy criterion.

Referring to Fig. 2.35d on p. 67 we note that, for this case, $\sigma_3 = 0$ and $\sigma_2 = \sigma_1/2$, as can be seen from Eq. (2.44) on p. 68. According to the distortion-energy criterion and referring to Eq. (2.52) on p. 69 for effective stress, we find

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that

$$\begin{aligned}\bar{\sigma} &= \frac{1}{\sqrt{2}}\left[\left(\sigma_1-\frac{\sigma_1}{2}\right)^2+\left(\frac{\sigma_1}{2}\right)^2+(\sigma_1)^2\right]^{1/2}\\ &= \frac{1}{\sqrt{2}}\left(\frac{1}{4}+\frac{1}{4}+1\right)^{1/2}\sigma_1\\ &= \frac{1}{\sqrt{2}}\left(\frac{\sqrt{3}}{\sqrt{2}}\right)\sigma_1=\frac{\sqrt{3}}{2}\sigma_1\end{aligned}$$

Note that for this case $\epsilon_3 = 0$. Since volume constancy is maintained during plastic deformation, we also have $\epsilon_3 = -\epsilon_1$. Substituting these into Eq. (2.54), the effective strain is found to be

$$\bar{\epsilon} = \left(\frac{2}{\sqrt{3}}\right)\epsilon_1$$

2.78 (a) Calculate the work done in expanding a 2-mm-thick spherical shell from a diameter of 100 mm to 140 mm, where the shell is made of a material for which $\sigma = 200+50\epsilon^{0.5}$ MPa. (b) Does your answer depend on the particular yield criterion used? Explain.

For this case, the membrane stresses are given by

$$\sigma_1 = \sigma_2 = \frac{pt}{2t}$$

and the strains are

$$\epsilon_1 = \epsilon_2 = \ln\left(\frac{f_r}{f_o}\right)$$

Note that we have a balanced (or equal) biaxial state of plane stress. Thus, the specific energy (for a perfectly-plastic material) will, according to either yield criteria, be

$$u = 2\sigma_1\epsilon_1 = 2Y\ln\left(\frac{r_f}{r_o}\right)$$

The work done will be

$$\begin{aligned}W &= (\text{Volume})(u)\\ &= \left(4\pi r_o^2 t_o\right)\left[2Y\ln\left(\frac{r_f}{r_o}\right)\right]\\ &= 8\pi Y r_o^2 t_o\ln\left(\frac{r_f}{r_o}\right)\end{aligned}$$

Using the pressure-volume method of work, we begin with the formula

$$W = \int p\,dV$$

where V is the volume of the sphere. We integrate this equation between the limits V_o and V_f, noting that

$$p = \frac{2tY}{r}$$

and

$$V = \frac{4\pi r^3}{3}$$

so that

$$dV = 4\pi r^2\,dr$$

Also, from volume constancy, we have

$$t = \frac{r_o^2 t_o}{r^2}$$

Combining these expressions, we obtain

$$W = 8\pi Y r_o^2 t_o\int_{r_o}^{r_f}\frac{dr}{r} = 8\pi Y r_o^2 t_o\ln\left(\frac{r_f}{r_o}\right)$$

which is the same expression obtained earlier. To obtain a numerical answer to this problem, note that Y should be replaced with an average value $\bar{Y}$. Also note that $\epsilon_1 = \epsilon_2 = \ln(140/100) = 0.336$. Thus,

$$\bar{Y} = 200+\frac{50(0.336)^{1.5}}{1.5} = 206\text{ MPa}$$

Hence the work done is

$$\begin{aligned}W &= 8\pi\bar{Y}r_o^2 t_o\ln\left(\frac{r_f}{r_o}\right)\\ &= 8\pi(206\times10^6)(0.1)^2(0.001)\ln(70/50)\\ &= 17.4\text{kN-m}\end{aligned}$$

The yield criterion used does not matter because this is equal biaxial tension; see the answer to Problem 2.68.

2.79 A cylindrical slug that has a diameter of 1 in. and is 1 in. high is placed at the center of a 2-in.-diameter cavity in a rigid die. (See the accompanying figure.) The slug is surrounded by a compressible matrix, the pressure of which is given by the relation

$$p_m = 40{,}000\frac{\Delta V}{V_{\text{om}}}\text{ psi}$$

where m denotes the matrix and V_{om} is the original volume of the compressible matrix. Both the slug and the matrix are being compressed by a piston and without any friction. The initial pressure on the matrix is zero, and the slug material has the true-stress-true-strain curve of $\sigma = 15{,}000\epsilon^{0.4}$.

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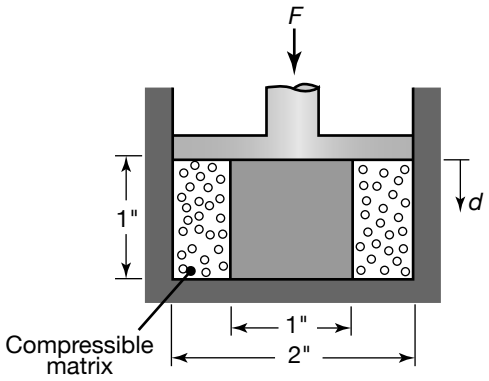


Obtain an expression for the force F versus piston travel d up to $d = 0.5$ in.

The total force, F, on the piston will be

$$F = F_w + F_m,$$

where the subscript w denotes the workpiece and m the matrix. As d increases, the matrix pressure increases, thus subjecting the slug to transverse compressive stresses on its circumference. Hence the slug will be subjected to triaxial compressive stresses, with $\sigma_2 = \sigma_3$. Using the maximum shear-stress criterion for simplicity, we have

$$\sigma_1 = \sigma + \sigma_2$$

where σ_1 is the required compressive stress on the slug, σ is the flow stress of the slug material corresponding to a given strain, and given as $\sigma = 15,000\epsilon^{0.4}$, and σ_2 is the compressive stress due to matrix pressure. Lets now determine the matrix pressure in terms of d.

The volume of the slug is equal to $\pi/4$ and the volume of the cavity when $d = 0$ is π. Hence the original volume of the matrix is $V_{om} = \frac{3}{4}\pi$. The volume of the matrix at any value of d is then

$$V_m = \pi(1 - d) - \frac{\pi}{4} = \pi\left(\frac{3}{4} - d\right) \text{ in}^3,$$

from which we obtain

$$\frac{\Delta V}{V_{om}} = \frac{V_{om} - V_m}{V_{om}} = \frac{4}{3}d.$$

Note that when $d = \frac{3}{4}$ in., the volume of the matrix becomes zero. The matrix pressure, hence σ_2, is now given by

$$\sigma_2 = \frac{4(40,000)}{3}d = \frac{160,000}{3}d \text{ (psi)}$$

The absolute value of the true strain in the slug is given by

$$\epsilon = \ln\frac{1}{1 - d},$$

with which we can determine the value of σ for any d. The cross-sectional area of the workpiece at any d is

$$A_w = \frac{\pi}{4(1 - d)} \text{ in}^2$$

and that of the matrix is

$$A_m = \pi - \frac{\pi}{4(1 - d)} \text{ in}^2$$

The required compressive stress on the slug is

$$\sigma_1 = \sigma + \sigma_2 = \sigma + \frac{160,000}{3}d.$$

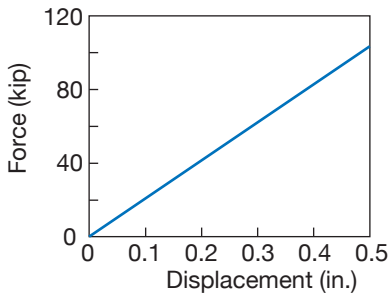
We may now write the total force on the piston as

$$F = A_w\left(\sigma + \frac{160,000}{3}d\right) + A_m\frac{160,000}{3}d \text{ lb.}$$

The following data gives some numerical results:

d (in.)	A_w (in^2)	ϵ	σ (psi)	F (lb)
0.1	0.872	0.105	6089	22,070
0.2	0.98	0.223	8230	41,590
0.3	1.121	0.357	9934	61,410
0.4	1.31	0.510	11,460	82,030
0.5	1.571	0.692	12,950	104,200

And the following plot shows the desired results.



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2.80 A specimen in the shape of a cube 20 mm on each side is being compressed without friction in a die cavity, as shown in Fig. 2.35d, where the width of the groove is 15 mm. Assume that the linearly strain-hardening material has the true-stress-true-strain curve given by $\sigma = 70 + 30\epsilon$ MPa. Calculate the compressive force required when the height of the specimen is at 3 mm, according to both yield criteria.

We note that the volume of the specimen is constant and can be expressed as

$$(20)(20)(20) = (h)(x)(x)$$

where x is the lateral dimensions assuming the specimen expands uniformly during compression. Since $h = 3$ mm, we have $x = 51.6$ mm. Thus, the specimen touches the walls and hence this becomes a plane-strain problem (see Fig. 2.35d on p. 67). The absolute value of the true strain is

$$\epsilon = \ln\left(\frac{20}{3}\right) = 1.90$$

We can now determine the flow stress, Y_f, of the material at this strain as

$$Y_f = 70 + 30(1.90) = 127 \text{ MPa}$$

The cross-sectional area on which the force is acting is

$$\text{Area} = (20)(20)(20)/3 = 2667 \text{ mm}^2$$

According to the maximum shear-stress criterion, we have $\sigma_1 = Y_f$, and thus

$$\text{Force} = (127)(2667) = 338 \text{ kN}$$

According to the distortion energy criterion, we have $\sigma_1 = 1.15Y_f$, or

$$\text{Force} = (1.15)(338) = 389 \text{ kN}.$$

2.81 Obtain expressions for the specific energy for a material for each of the stress-strain curves shown in Fig. 2.7, similar to those shown in Section 2.12.

Equation (2.59) on p. 71 gives the specific energy as

$$u = \int_0^{\epsilon_1} \sigma \, d\epsilon$$

(a) For a perfectly-elastic material as shown in Fig 2.7a on p. 40, this expression becomes

$$u = \int_0^{\epsilon_1} E\epsilon \, d\epsilon = E\left(\frac{\epsilon^2}{2}\right)_0^{\epsilon_1} = \frac{E\epsilon_1^2}{2}$$

(b) For a rigid, perfectly-plastic material as shown in Fig. 2.7b, this is

$$u = \int_0^{\epsilon_1} Y \, d\epsilon = Y\,(\epsilon)_0^{\epsilon_1} = Y\epsilon_1$$

(c) For an elastic, perfectly plastic material, this is identical to an elastic material for $\epsilon_1 < Y/E$, and for $\epsilon_1 > Y/E$ it is

$$\begin{aligned} u &= \int_0^{\epsilon_1} \sigma \, d\epsilon = \int_0^{Y/E} E\epsilon \, d\epsilon + \int_{Y/E}^{\epsilon_1} Y \, d\epsilon \\ &= \frac{E}{2}\left(\frac{Y}{E}\right)^2 + Y\left(\epsilon_1 - \frac{Y}{E}\right) \\ &= \frac{Y^2}{2E} + Y\epsilon_1 - \frac{Y^2}{E} = Y\left(\epsilon_1 - \frac{Y}{2E}\right) \end{aligned}$$

(d) For a rigid, linearly strain hardening material, the specific energy is

$$u = \int_0^{\epsilon_1} (Y + E_p\epsilon) \, d\epsilon = Y\epsilon_1 + \frac{E_p\epsilon_1^2}{2}$$

(e) For an elastic, linear strain hardening material, the specific energy is identical to an elastic material for $\epsilon_1 < Y/E$ and for $\epsilon_1 > Y/E$ it is

$$\begin{aligned} u &= \int_0^{\epsilon_1} \left[Y + E_p\left(\epsilon - \frac{Y}{E}\right)\right] d\epsilon \\ &= \int_0^{\epsilon_1} \left[Y\left(1 - \frac{E_p}{E}\right) + E_p\epsilon\right] d\epsilon \\ &= Y\left(1 - \frac{E_p}{E}\right)\epsilon_1 + \frac{E_p\epsilon_1^2}{2} \end{aligned}$$

2.82 A material with a yield stress of 70 MPa is subjected to three principal (normal) stresses of σ_1, $\sigma_2 = 0$, and $\sigma_3 = -\sigma_1/2$. What is the value of σ_1 when the metal yields according to the von Mises criterion? What if $\sigma_2 = \sigma_1/3$?

The distortion-energy criterion, given by Eq. (2.37) on p. 64, is

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$$

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Substituting $Y = 70$ MPa and σ_1, $\sigma_2 = 0$ and $\sigma_3 = -\sigma_1/2$, we have

$$2(70)^2 = (\sigma_1)^2 + \left(-\frac{\sigma_1}{2}\right)^2 + \left(-\frac{\sigma_1}{2} - \sigma_1\right)^2$$

thus,

$$\sigma_1 = 52.9 \text{ MPa}$$

If $Y = 70$ MPa and σ_1, $\sigma_2 = \sigma_1/3$ and $\sigma_3 = -\sigma_1/2$ is the stress state, then

$$\begin{aligned} 2(70)^2 &= \left(\sigma_1 - \frac{\sigma_1}{3}\right)^2 + \left(\frac{\sigma_1}{3} - \frac{\sigma_1}{2}\right)^2 \\ &\quad + \left(-\frac{\sigma_1}{2} - \sigma_1\right)^2 = 2.72\sigma_1^2 \end{aligned}$$

Thus, $\sigma_1 = 60.0$ MPa. Therefore, the stress level to initiate yielding actually increases when σ_2 is increased.

2.83 A steel plate has the dimensions 100 mm × 100 mm × 5 mm thick. It is subjected to biaxial tension of $\sigma_1 = \sigma_2$, with the stress in the thickness direction of $\sigma_3 = 0$. What is the largest possible change in volume at yielding, using the von Mises criterion? What would this change in volume be if the plate were made of copper?

From Table 2.1 on p. 32, it is noted that for steel we can use $E = 200$ GPa and $\nu = 0.30$. For a stress state of $\sigma_1 = \sigma_2$ and $\sigma_3 = 0$, the von Mises criterion predicts that at yielding,

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$$

or

$$(\sigma_1 - \sigma_1)^2 + (\sigma_1 - 0)^2 + (0 - \sigma_1)^2 = 2Y^2$$

Resulting in $\sigma_1 = Y$. Equation (2.47) gives:

$$\begin{aligned} \Delta &= \frac{1-2\nu}{E}(\sigma_x + \sigma_y + \sigma_z) \\ &= \frac{1-2(0.3)}{200 \text{ GPa}}[(350 \text{ MPa}) + (350 \text{ MPa}] \\ &= = 0.0014 \end{aligned}$$

Since the original volume is $(100)(100)(5) = 50{,}000$ mm^3, the stressed volume is 50,070 mm^3, or the volume change is 70 mm^3.

For copper, we have $E = 125$ GPa and $\nu = 0.34$. Following the same derivation, the dilatation for copper is 0.0006144; the stressed volume is 50,031 mm^3 and thus the change in volume is 31 mm^3.

2.84 A 50-mm-wide, 1-mm-thick strip is rolled to a final thickness of 0.5 mm. It is noted that the strip has increased in width to 52 mm. What is the strain in the rolling direction?

The thickness strain is

$$\epsilon_t = \ln\left(\frac{l}{l_o}\right) = \ln\left(\frac{0.5 \text{ mm}}{1 \text{ mm}}\right) = -0.693$$

The width strain is

$$\epsilon_w = \ln\left(\frac{l}{l_o}\right) = \ln\left(\frac{52 \text{ mm}}{50 \text{ mm}}\right) = 0.0392$$

Therefore, from Eq. (2.48), the strain in the rolling (or longitudinal) direction is $\epsilon_l = 0 - 0.0392 + 0.693 = 0.654$.

2.85 An aluminum alloy yields at a stress of 50 MPa in uniaxial tension. If this material is subjected to the stresses $\sigma_1 = 25$ MPa, $\sigma_2 = 15$ MPa and $\sigma_3 = -26$ MPa, will it yield? Explain.

According to the maximum shear-stress criterion, the effective stress is given by Eq. (2.51) on p. 69 as:

$$\bar{\sigma} = \sigma_1 - \sigma_3 = 25 - (-26) = 51 \text{ MPa}$$

However, according to the distortion-energy criterion, the effective stress is given by Eq. (2.52) on p. 69 as:

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

or

$$\bar{\sigma} = \sqrt{\frac{(25-15)^2 + (15+26)^2 + (-26-25)^2}{2}}$$

or $\bar{\sigma} = 46.8$ MPa. Therefore, the effective stress is higher than the yield stress for the maximum shear-stress criterion, and lower than the yield stress for the distortion-energy criterion. It is impossible to state whether or not the material will yield at this stress state. An accurate statement would be that yielding is imminent, if it is not already occurring.

2.86 A cylindrical specimen 1-in. in diameter and 1-in. high is being compressed by dropping a weight of 200 lb on it from a certain height. After deformation, it is found that the temperature rise in the specimen is 300 °F. Assuming

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no heat loss and no friction, calculate the final height of the specimen, using the following data for the material: $K = 30,000$ psi, $n = 0.5$, density = 0.1 lb/in^3, and specific heat = 0.3 BTU/lb·°F.

This problem uses the same approach as in Example 2.8. The volume of the specimen is

$$V = \frac{\pi d^2 h}{4} = \frac{\pi(1)^2(1)}{4} = 0.785 \text{ in}^3$$

The expression for heat is given by

$$\begin{aligned} \text{Heat} &= c_p \rho V \Delta T \\ &= (0.3)(0.1)(0.785)(300)(778) \\ &= 5500\text{ft-lb} = 66,000 \text{ in-lb}. \end{aligned}$$

where the unit conversion 778 ft-lb = 1 BTU has been applied. Since, ideally,

$$\begin{aligned} \text{Heat} = \text{Work} &= Vu = V\frac{K\epsilon^{n+1}}{n+1} \\ &= (0.785)\frac{(30,000)\epsilon^{1.5}}{1.5} \end{aligned}$$

Solving for ϵ,

$$\epsilon^{1.5} = \frac{1.5(66,000)}{(0.785)(30,000)} = 4.20$$

Therefore, $\epsilon = 2.60$. Using absolute values, we have

$$\ln\left(\frac{h_o}{h_f}\right) = \ln\left(\frac{1 \text{ in.}}{h_f}\right) = 2.60$$

Solving for h_f gives $h_f = 0.074$ in.

2.87 A solid cylindrical specimen 100-mm high is compressed to a final height of 40 mm in two steps between frictionless platens; after the first step the cylinder is 70 mm high. Calculate the engineering strain and the true strain for both steps, compare them, and comment on your observations.

In the first step, we note that $h_o = 100$ mm and $h_1 = 70$ mm, so that from Eq. (2.1) on p. 30,

$$e_1 = \frac{h_1 - h_o}{h_o} = \frac{70 - 100}{100} = -0.300$$

and from Eq. (2.9) on p. 35,

$$\epsilon_1 = \ln\left(\frac{h_1}{h_o}\right) = \ln\left(\frac{70}{100}\right) = -0.357$$

Similarly, for the second step where $h_1 = 70$ mm and $h_2 = 40$ mm,

$$e_2 = \frac{h_2 - h_1}{h_1} = \frac{40 - 70}{70} = -0.429$$

$$\epsilon_2 = \ln\left(\frac{h_2}{h_1}\right) = \ln\left(\frac{40}{70}\right) = -0.560$$

Note that if the operation were conducted in one step, the following would result:

$$e = \frac{h_2 - h_o}{h_o} = \frac{40 - 100}{100} = -0.6$$

$$\epsilon = \ln\left(\frac{h_2}{h_o}\right) = \ln\left(\frac{40}{100}\right) = -0.916$$

As was shown in Problem 2.46, this indicates that the true strains are additive while the engineering strains are not.

2.88 Assume that the specimen in Problem 2.87 has an initial diameter of 80 mm and is made of 1100-O aluminum. Determine the load required for each step.

From volume constancy, we calculate

$$d_1 = d_o\sqrt{\frac{h_o}{h_1}} = 80\sqrt{\frac{100}{70}} = 95.6 \text{ mm}$$

$$d_2 = d_o\sqrt{\frac{h_o}{h_2}} = 80\sqrt{\frac{100}{40}} = 126.5 \text{ mm}$$

Based on these diameters the cross-sectional area at the steps is calculated as:

$$A_1 = \frac{\pi}{4}d_1^2 = 7181 \text{ mm}^2$$

$$A_2 = \frac{\pi}{4}d_2^2 = 12,566 \text{ mm}^2$$

As calculated in Problem 2.87, $\epsilon_1 = 0.357$ and $\epsilon_{\text{total}} = 0.916$. Note that for 1100-O aluminum, $K = 180$ MPa and $n = 0.20$ (see Table 2.3 on p. 37) so that Eq. (2.11) on p. 35 yields

$$\sigma_1 = 180(0.357)^{0.20} = 146.5 \text{ MPa}$$

$$\sigma_2 = 180(0.916)^{0.20} = 176.9 \text{ Mpa}$$

Therefore, the loads are calculated as:

$$P_1 = \sigma_1 A_1 = (146.5)(7181) = 1050 \text{ kN}$$

$$P_2 = (176.9)(12,566) = 2223 \text{ kN}$$

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2.89 Determine the specific energy and actual energy expended for the entire process described in the preceding two problems.

From Eq. (2.60) on p. 71 and using $\epsilon_{\text{total}} = 0.916$, $K = 180$ MPa and $n = 0.20$, we have

$$u = \frac{K\epsilon^{n+1}}{n+1} = \frac{(180)(0.916)^{1.2}}{1.2} = 135 \text{ MPa}$$

2.90 A metal has a strain hardening exponent of 0.22. At a true strain of 0.2, the true stress is 20,000 psi. (a) Determine the stress-strain relationship for this material. (b) Determine the ultimate tensile strength for this material.

This solution follows the same approach as in Example 2.1. From Eq. (2.11) on p. 35, and recognizing that $n = 0.22$ and $\sigma = 20,000$ psi for $\epsilon = 0.20$,

$$\sigma = K\epsilon^n \quad \rightarrow \quad 20,000 = K(0.20)^{0.22}$$

or $K = 28,500$ psi. Therefore, the stress-strain relationship for this material is

$$\sigma = 28,500\epsilon^{0.22} \text{ psi}$$

To determine the ultimate tensile strength for the material, realize that the strain at necking is equal to the strain hardening exponent, or $\epsilon = n$. Therefore,

$$\sigma_{\text{ult}} = K(n)^n = 28,500(0.22)^{0.22} = 20,400 \text{ psi}$$

The cross-sectional area at the onset of necking is obtained from

$$\ln\left(\frac{A_o}{A_{\text{neck}}}\right) = n = 0.22$$

Consequently,

$$A_{\text{neck}} = A_o e^{-0.22}$$

and the maximum load is

$$P = \sigma A = \sigma_{\text{ult}} A_{\text{neck}}.$$

Hence,

$$P = (20,400)(A_o)e^{-0.22} = 16,370A_o$$

Since UTS$= P/A_o$, we have

$$\text{UTS} = \frac{16,370A_o}{A_o} = 16,370 \text{ psi}$$

2.91 The area of each face of a metal cube is 400 m^2, and the metal has a shear yield stress, k, of 140 MPa. Compressive loads of 40 kN and 80 kN are applied at different faces (say in the x- and y-directions). What must be the compressive load applied to the z-direction to cause yielding according to the Tresca criterion? Assume a frictionless condition.

Since the area of each face is 400 mm^2, the stresses in the x- and y- directions are

$$\sigma_x = -\frac{40,000}{400} = -100 \text{ MPa}$$

$$\sigma_y = -\frac{80,000}{400} = -200 \text{ MPa}$$

where the negative sign indicates that the stresses are compressive. If the Tresca criterion is used, then Eq. (2.36) on p. 64 gives

$$\sigma_{\max} - \sigma_{\min} = Y = 2k = 280 \text{ MPa}$$

It is stated that σ_3 is compressive, and is therefore negative. Note that if σ_3 is zero, then the material does not yield because $\sigma_{\max} - \sigma_{\min} = 0 - (-200) = 200$ MPa < 280 MPa. Therefore, σ_3 must be lower than σ_2, and is calculated from:

$$\sigma_{\max} - \sigma_{\min} = \sigma_1 - \sigma_3 = 280 \text{ MPa}$$

or

$$\sigma_3 = \sigma_1 - 280 = -100 - 280 = -380 \text{ MPa}$$

2.92 A tensile force of 9 kN is applied to the ends of a solid bar of 6.35 mm diameter. Under load, the diameter reduces to 5.00 mm. Assuming uniform deformation and volume constancy, (a) determine the engineering stress and strain, (b) determine the true stress and strain, (c) if the original bar had been subjected to a true stress of 345 MPa and the resulting diameter was 5.60 mm, what are the engineering stress and engineering strain for this condition?

First note that, in this case, $d_o = 6.35$ mm, $d_f = 5.00$ mm, P=9000 N, and from volume constancy,

$$l_o d_o^2 = l_f d_f^2 \quad \rightarrow \quad \frac{l_f}{l_o} = \frac{d_o^2}{d_f^2} = \frac{6.35^2}{5.00^2} = 1.613$$

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(a) The engineering stress is calculated from Eq. (2.3) on p. 30 as:

$$\sigma = \frac{P}{A_o} = \frac{9000}{\frac{\pi}{4}(6.35)^2} = 284 \text{ MPa}$$

and the engineering strain is calculated from Eq. (2.1) on p. 30 as:

$$e = \frac{l - l_o}{l_o} = \frac{l_f}{l_o} - 1 = 1.613 - 1 = 0.613$$

(b) The true stress is calculated from Eq. (2.8) on p. 34 as:

$$\sigma = \frac{P}{A} = \frac{9000}{\frac{\pi}{4}(5.00)^2} = 458 \text{ MPa}$$

and the true strain is calculated from Eq. (2.9) on p. 35 as:

$$\epsilon = \ln\left(\frac{l_f}{l_o}\right) = \ln 1.613 = 0.478$$

(c) If the final diameter is $d_f = 5.60$ mm, then the final area is $A_f = \frac{\pi}{4}d_f^2 = 24.63$ mm^2. If the true stress is 345 MPa, then

$$P = \sigma A = (345)(24.63) = 8497 \approx 8500 \text{ N}$$

Therefore, the engineering stress is calculated as before as

$$\sigma = \frac{P}{A_o} = \frac{8500}{\frac{\pi}{4}(6.35)^2} = 268 \text{ MPa}$$

Similarly, from volume constancy,

$$\frac{l_f}{l_o} = \frac{d_o^2}{d_f^2} = \frac{6.35^2}{5.60^2} = 1.286$$

Therefore, the engineering strain is

$$e = \frac{l_f}{l_o} - 1 = 1.286 - 1 = 0.286$$

2.93 Two identical specimens 10-mm in diameter and with test sections 25 mm long are made of 1112 steel. One is in the as-received condition and the other is annealed. What will be the true strain when necking begins, and what will be the elongation of these samples at that instant? What is the ultimate tensile strength for these samples?

This problem uses a similar approach as for Example 2.1. First, we note from Table 2.3 on p. 37 that for cold-rolled 1112 steel, $K = 760$ MPa and $n = 0.08$. Also, the initial cross-sectional area is $A_o = \frac{\pi}{4}(10)^2 = 78.5$ mm^2. For annealed 1112 steel, $K = 760$ MPa and $n = 0.19$. At necking, $\epsilon = n$, so that the strain will be $\epsilon = 0.08$ for the cold-rolled steel and $\epsilon = 0.19$ for the annealed steel. For the cold-rolled steel, the final length is given by Eq. (2.9) on p. 35 as

$$\epsilon = n = \ln\left(\frac{l}{l_o}\right)$$

Solving for l,

$$l = e^n l_o = e^{0.08}(25) = 27.08 \text{ mm}$$

The elongation is, from Eq. (2.6),

$$\text{Elongation} = \frac{l_f - l_o}{l_o} \times 100 = \frac{27.08 - 25}{25} \times 100$$

or 8.32 %. To calculate the ultimate strength, we can write, for the cold-rolled steel,

$$\text{UTS}_{\text{true}} = Kn^n = 760(0.08)^{0.08} = 621 \text{ MPa}$$

As in Example 2.1, we calculate the load at necking as:

$$P = \text{UTS}_{\text{true}} A_o e^{-n}$$

So that

$$\text{UTS} = \frac{P}{A_o} = \frac{\text{UTS}_{\text{true}} A_o e^{-n}}{A_o} = \text{UTS}_{\text{true}} e^{-n}$$

This expression is evaluated as

$$\text{UTS} = (621)e^{-0.08} = 573 \text{ MPa}$$

Repeating these calculations for the annealed specimen yields $l = 30.23$ mm, elongation = 20.9%, and UTS= 458 MPa.

2.94 During the production of a part, a metal with a yield strength of 110 MPa is subjected to a stress state σ_1, $\sigma_2 = \sigma_1/3$, $\sigma_3 = 0$. Sketch the Mohr's circle diagram for this stress state. Determine the stress σ_1 necessary to cause yielding by the maximum shear stress and the von Mises criteria.

For the stress state of σ_1, $\sigma_1/3$, 0 the following figure the three-dimensional Mohr's circle:

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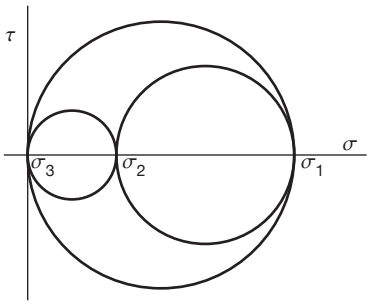


For the von Mises criterion, Eq. (2.37) on p. 64 gives:

$$\begin{aligned} 2Y^2 &= (\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2 \\ &= \left(\sigma_1-\frac{\sigma_1}{3}\right)^2+\left(\frac{\sigma_1}{3}-0\right)^2+(0-\sigma_1)^2 \\ &= \frac{4}{9}\sigma_1^2+\frac{1}{9}\sigma_1^2+\sigma_1^2=\frac{14}{9}\sigma_1^2 \end{aligned}$$

Solving for σ_1 gives $\sigma_1 = 125$ MPa. According to the Tresca criterion, Eq. (2.36) on p. 64 on p. 64 gives

$$\sigma_1-\sigma_3=\sigma_1=0=Y$$

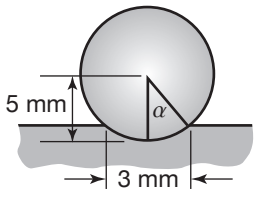
or $\sigma_1 = 110$ MPa.

2.95 Estimate the depth of penetration in a Brinell hardness test using 500-kg load, when the sample is a cold-worked aluminum with a yield stress of 200 MPa.

Note from Fig. 2.24 on p. 55 that for cold-worked aluminum with a yield stress of 200 MPa, the Brinell hardness is around 65 kg/mm^2. From Fig. 2.22 on p. 52, we can estimate the diameter of the indentation from the expression:

$$\text{HB}=\frac{2P}{(\pi D)(D-\sqrt{D^2-d^2})}$$

from which we find that $d = 3.091$ mm for $D = 10mm$. To calculate the depth of penetration, consider the following sketch:



Because the radius is 5 mm and one-half the penetration diameter is 1.5 mm, we can obtain α as

$$\alpha=\sin^{-1}\left(\frac{1.5}{5}\right)=17.5^\circ$$

The depth of penetration, t, can be obtained from

$$t=5-5\cos\alpha=5-5\cos 17.5^\circ=0.23 \text{ mm}$$

2.96 The following data are taken from a stainless steel tension-test specimen:

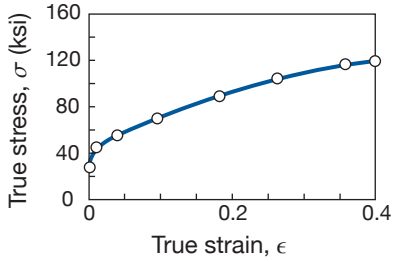
Load, P (lb)	Extension, Δl (in.)
1600	0
2500	0.02
3000	0.08
3600	0.20
4200	0.40
4500	0.60
4600 (max)	0.86
4586 (fracture)	0.98

Also, $A_o = 0.056$ in^2, $A_f = 0.016$ in^2, $l_o = 2$ in. Plot the true stress-true strain curve for the material.

The following are calculated from Eqs. (2.6), (2.9), (2.10), and (2.8) on pp. 33-35:

Δl	l	ϵ	A (in^2)	σ (ksi)
0	2.0	0	0.056	28.5
0.02	2.02	0.00995	0.0554	45.1
0.08	2.08	0.0392	0.0538	55.7
0.2	2.2	0.0953	0.0509	70.7
0.4	2.4	0.182	0.0467	90.
0.6	2.6	0.262	0.0431	104
0.86	2.86	0.357	0.0392	117
0.98	2.98	0.399	0.0376	120

The true stress-true strain curve is then plotted as follows:



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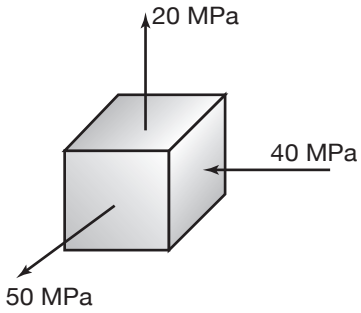
2.97 A metal is yielding plastically under the stress state shown in the accompanying figure.



(a) Label the principal axes according to their proper numerical convention (1, 2, 3).

(b) What is the yield stress using the Tresca criterion?

(c) What if the von Mises criterion is used?

(d) The stress state causes measured strains of $\epsilon_1 = 0.4$ and $\epsilon_2 = 0.2$, with ϵ_3 not being measured. What is the value of ϵ_3?

(a) Since $\sigma_1 \geq \sigma_2 \geq \sigma_3$, then from the figure $\sigma_1 = 50$ MPa, $\sigma_2 = 20$ MPa and $\sigma_3 = -40$ MPa.

(b) The yield stress using the Tresca criterion is given by Eq. (2.36) as

$$\sigma_{\max} - \sigma_{\min} = Y$$

So that

$$Y = 50 \text{ MPa} - (-40 \text{ MPa}) = 90 \text{ MPa}$$

(c) If the von Mises criterion is used, then Eq. (2.37) on p. 64 gives

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$$

or

$$2Y^2 = (50 - 20)^2 + (20 + 40)^2 + (50 + 40)^2$$

or

$$2Y^2 = 12,600$$

which is solved as $Y = 79.4$ MPa.

(d) If the material is deforming plastically, then from Eq. (2.48) on p. 69,

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0.4 + 0.2 + \epsilon_3 = 0$$

or $\epsilon_3 = -0.6$.

2.98 It has been proposed to modify the von Mises yield criterion as:

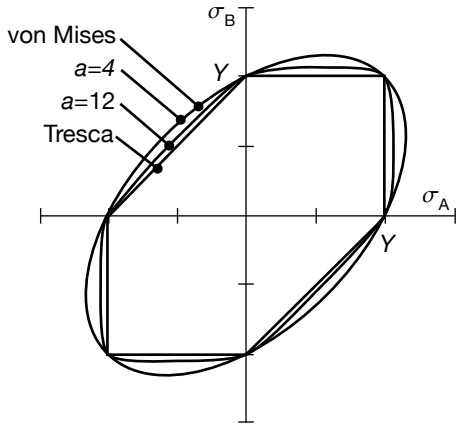
$$(\sigma_1 - \sigma_2)^a + (\sigma_2 - \sigma_3)^a + (\sigma_3 - \sigma_1)^a = C$$

where C is a constant and a is an even integer larger than 2. Plot this yield criterion for $a = 4$ and $a = 12$, along with the Tresca and von Mises criteria, in plane stress. (*Hint:* See Fig. 2.36 on p. 67).

For plane stress, one of the stresses, say σ_3, is zero, and the other stresses are σ_A and σ_B. The yield criterion is then

$$(\sigma_A - \sigma_B)^a + (\sigma_B)^a + (\sigma_A)^a = C$$

For uniaxial tension, $\sigma_A = Y$ and $\sigma_B = 0$ so that $C = 2Y^a$. These equations are difficult to solve by hand; the following solution was obtained using a mathematical programming package:



Note that the solution for $a = 2$ (von Mises) and $a = 4$ are so close that they cannot be distinguished in the plot. When zoomed into a portion of the curve, one would see that the $a = 4$ curve lies between the von Mises curve and the $a = 12$ curve.

2.99 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the student, and has been found to be a very valuable homework problem.

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Chapter 3

Structure and Manufacturing Properties of Metals

Questions

3.1 What is the difference between a unit cell and a single crystal?

A unit cell is the smallest group of atoms showing the characteristic lattice structure of a particular metal. A single crystal consists of a number of unit cells; some examples are whiskers, chips for semiconductor devices, and turbine blades.

3.2 Explain why we should study the crystal structure of metals.

By studying the crystal structure of metals, information about various properties can be inferred. By relating structure to properties, one can predict processing behavior or select appropriate applications for a metal. Metals with face-centered cubic structure, for example, tend to be ductile whereas hexagonal close-packed metals tend to be brittle.

3.3 What effects does recrystallization have on the properties of metals?

As shown in Figs. 3.17 on p. 96 and 3.18 on p. 97, strength and hardness are reduced, ductility is increased, and residual stresses are relieved.

3.4 What is the significance of a slip system?

The greater the number of slip systems, the higher the ductility of the metal. Also, the slip system and the number of active slip systems give direct understanding of the material's plastic behavior. For example, an hcp material has few slip systems. Thus, in a bulk material, few grains will be preferentially oriented with respect to a slip system and high stresses will be required to initiate plastic deformation. On the other hand, fcc materials, have many slip systems and thus a lower stress will be required for plastic deformation. See also Section 3.3.1 starting on p. 87.

3.5 Explain what is meant by structure-sensitive and structure-insensitive properties of metals.

As described in Section 3.3.3 starting on p. 89, those properties that depend on the structure of a metal are known as *structure-sensitive* properties (yield and fracture strength, electrical conductivity). Those that are not (other physical properties and elastic constants) are called *structure-insensitive* properties.

3.6 What is the relationship between nucleation rate and the number of grains per unit volume of a metal?

This relationship is described at the beginning of Section 3.4 starting on p. 91. Generally, rapid cooling produces smaller grains, whereas slow cooling produces larger grains.

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3.7 Explain the difference between recovery and recrystallization.

These phenomena are described in Section 3.6 on p. 96. Recovery involves relief of residual stresses, reduction in the number of dislocations, and increase in ductility. In recrystalization, new equiaxed and stress-free grains are formed, replacing the older grains.

3.8 (a) Is it possible for two pieces of the same metal to have different recrystallization temperatures? Explain. (b) Is it possible for recrystallization to take place in some regions of a workpiece before other regions do in the same workpiece? Explain.

(a) Two pieces of the same metal can have different recrystallization temperatures if the pieces have been cold worked to different amounts. The piece that was cold worked to a greater extent will have more stored energy to drive the recrystallization process, and hence its recrystallization temperature will be lower. See also Fig. 3.18 on p. 97.

(b) Recrystallization may occur in some regions before others if

i. the workpiece was unevenly worked, as is generally the case in deformation processing of materials, since varying amounts of cold work have different recrystallization temperatures, or

ii. the part has varying thicknesses; the thinner sections will heat up to the recrystallization temperature faster.

3.9 Describe why different crystal structures exhibit different strengths and ductilities.

Different crystal structures have different slip systems, which consist of a slip plane (the closest packed plane) and a slip direction (the close-packed direction). The fcc structure has 12 slip systems, bcc has 48, and hcp has 3. The ductility of a metal depends on how many of the slip systems can be operative. In general, fcc and bcc structures possess higher ductility than hcp structures, because they have more slip systems. The shear strength of a metal decreases for decreasing b/a ratio (b is inversely proportional to atomic density in the slip plane and a is the plane spacing), and the b/a ratio depends on the slip system of the chemical structure. (See also Section 3.3.1 starting on p. 87.)

3.10 Explain the difference between preferred orientation and mechanical fibering.

Preferred orientation is anisotropic behavior in a polycrystalline workpiece that has crystals aligned in nonrandom orientations. Crystals become oriented nonrandomly in a workpiece when it is deformed, because the slip direction of a crystal tends to align along the general deformation direction. Mechanical fibering is caused by the alignment of impurities, inclusions, or voids during plastic working of a metal; hence, the properties vary with the relative orientation of the stress applied to the orientation of the defect. (See also *preferred orientation* in Section 3.5 on p. 95.)

3.11 Give some analogies to mechanical fibering (such as layers of thin dough sprinkled with flour).

This is an open-ended problem with many acceptable answers. Some examples are plywood, laminated products (such as countertops), winter clothing, pastry with layers of cream or jam, and pasta dishes with layers of pasta and cheese.

3.12 A cold-worked piece of metal has been recrystallized. When tested, it is found to be anisotropic. Explain the probable reason for this behavior.

The anisotropy of the workpiece is likely due to preferred orientation resulting from the recrystallization process. Copper is an example of a metal that has a very strong preferred orientation after annealing. As shown in Fig. 3.19 on p. 97, no recrystallization occurs below a critical deformation, being typically five percent.

3.13 Does recrystallization completely eliminate mechanical fibering in a workpiece? Explain.

Mechanical fibering involves the alignment of impurities, inclusions, and voids in the workpiece during deformation. Recrystallization generally modifies the grain structure, but will not eliminate mechanical fibering.

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3.14 Explain why we may have to be concerned with the orange-peel effect on metal surfaces.

Orange peel not only influences surface appearance of parts, which may or may not be desirable, but also affects their surface characteristics such as friction, wear, lubrication, and corrosion and electrical properties, as well as subsequent finishing, coating, and painting operations. (See also *surface roughness in practice* in Section 4.3 on p. 137.)

3.15 How can you tell the difference between two parts made of the same metal, one shaped by cold working and the other by hot working? Explain the differences you might observe. Note that there are several methods that can be used to determine the differences between the two parts.

Some of the methods of distinguishing hot vs. cold worked parts are:

(a) The surface finish of the cold-worked part would be smoother than the hot-worked part, and possibly shinier.

(b) If hardness values could be taken on the parts, the cold-worked part would be harder.

(c) The cold-worked part would likely contain residual stresses and exhibit anisotropic behavior.

(d) Metallographic examination of the parts can be made: the hot-worked part would generally have equiaxed grains due to recrystallization, while the cold-worked part would have grains elongated in the general direction of deformation.

(e) The two parts can be subjected to mechanical testing and their properties compared.

3.16 Explain why the strength of a polycrystalline metal at room temperature decreases as its grain size increases.

Strength increases as more entanglements of dislocations take place with grain boundaries and with each other. Metals with larger grains have less grain-boundary area per unit volume, and hence they are not be able to generate as many entanglements at grain boundaries, thus the strength will be lower. (See also Eq. (3.8) on p. 92.)

3.17 What is the significance of some metals, such as lead and tin, having recrystallization temperatures at about room temperature?

For these metals, room temperature is sufficiently high for recrystallization to occur without heating. These metals can be cold worked to large extent without requiring a recrystallization cycle to restore their ductility, hence formability. However, as the strain rate increases, their strength at room temperature increases because the metal has less time to recrystallize, thus exhibiting a strain hardening behavior.

3.18 You are given a deck of playing cards held together with a rubber band. Which of the material-behavior phenomena described in this chapter could you demonstrate with this setup? What would be the effects of increasing the number of rubber bands holding the cards together? Explain. (*Hint:* Inspect Figs. 3.5 and 3.7.)

The following demonstrations can be made with a deck of cards sliding against each other:

(a) Slip planes; permanent slip of cards with no rubber band, similar to that shown in Fig. 3.5a on p. 86.

(b) Surface roughness that develops along the edges of the deck of cards, similar to the lower part of Fig. 3.7 on p. 88.

(c) Friction between the cards, simulating the shear stress required to cause slip, similar to Fig. 3.5 on p. 86. Friction between the cards can be decreased using talcum powder, or increased by moisture or soft glue (that has not set yet).

(d) Failure by slip, similar to Fig. 3.22b on p. 99.

(e) Presence of a rubber band indicates elastic behavior and recovery when unloaded.

(f) The greater the number of rubber bands, the higher the shear modulus, G, which is related to the elastic modulus, E.

(g) The deck of cards is highly anisotropic.

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3.19 Using the information given in Chapters 2 and 3, list and describe the conditions that induce brittle fracture in an otherwise ductile piece of metal.

Brittle fracture can be induced typically by:

(a) high deformation rates,

(b) the presence of stress concentrations, such as notches and cracks,

(c) state of stress, especially high hydrostatic tension components,

(d) radiation damage, and

(e) lower temperatures, particularly for metals with bcc structure. In each case, the stress required to cause yielding is raised above the stress needed to cause failure, or the stress needed for crack propagation is below the yield stress of the metal (as with stress concentrations).

3.20 Make a list of metals that would be suitable for a (1) paper clip, (2) bicycle frame, (3) razor blade, (4) battery cable, and (5) gas-turbine blade. Explain your reasoning.

In the selection of materials for these applications, the particular requirements that are significant to these components are briefly outlined as follows:

(a) Yield stress, elastic modulus, corrosion resistance.

(b) Strength, toughness, wear resistance, density.

(c) Strength, resistance to corrosion and wear.

(d) Yield stress, toughness, elastic modulus, corrosion resistance, and electrical conductivity.

(e) Strength, creep resistance, resistance to various types of wear, and corrosion resistance at high temperature.

Students are encouraged to suggest a variety of metals and discuss the relative advantages and limitations with regard to particular applications.

3.21 Explain the advantages and limitations of cold, warm, and hot working of metals, respectively.

These are explained briefly in Section 3.7 on p. 98. Basically, cold working has the advantages of refining the materials grain structure while increasing mechanical properties such as strength, but it does result in anisotropy and reduced ductility. Hot working does not result in strengthening of the workpiece, but the ductility of the workpiece is preserved, and there is little or no anisotropy. Warm working is a compromise.

3.22 Explain why parts may crack when suddenly subjected to extremes of temperature.

Thermal stresses result from temperature gradients in a material; the temperature will vary significantly throughout the part when subjected to extremes of temperature. The higher the temperature gradient, the more severe thermal stresses to which the part will be subjected, and the higher stresses will increase the probability of cracking. This is particularly important in brittle and notch-sensitive materials. (See also Section 3.9.5 starting on p. 107 regarding the role of coefficient of thermal expansion and thermal conductivity in development of thermal stresses.)

3.23 From your own experience and observations, list three applications each for the following metals and their alloys: (1) steel, (2) aluminum, (3) copper, (4) magnesium, and (5) gold.

There are numerous acceptable answers, including:

(a) steel: automobile bodies, structural members (buildings, boilers, machinery), fasteners, springs, bearings, knives.

(b) aluminum: aircraft bodies, baseball bats, cookware, beverage containers, automotive pistons.

(c) copper: electrical wire, cookware, battery cable terminals, printed circuit boards.

(d) lead: batteries, toy soldiers, solders, glass crystal.

(e) gold: jewelry, electrical connections, tooth fillings, coins, medals.

3.24 List three applications that are not suitable for each of the following metals and their alloys:

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(1) steel, (2) aluminum, (3) copper, (4) magnesium, and (5) gold.

There are several acceptable answers, including:

(a) steel: electrical contacts, aircraft fuselage, car tire, portable computer case.

(b) aluminum: cutting tools, shafts, gears, flywheels.

(c) copper: aircraft fuselage, bridges, submarine, toys.

(d) lead: toys, cookware, aircraft structural components, automobile body panels.

(e) gold: any part or component with a large mass and that requires strength and stiffness.

3.25 Name products that would not have been developed to their advanced stages, as we find them today, if alloys with high strength and corrosion and creep resistance at elevated temperatures had not been developed.

Some simple examples are jet engines and furnaces. The student is encouraged to cite numerous other examples.

3.26 Inspect several metal products and components and make an educated guess as to what materials they are made from. Give reasons for your guess. If you list two or more possibilities, explain your reasoning.

This is an open-ended problem and is a good topic for group discussion in class. Some examples, such as an aluminum baseball bat or beverage can, can be cited and students can be asked why they believe the material is aluminum.

3.27 List three engineering applications each for which the following physical properties would be desirable: (1) high density, (2) low melting point, and (3) high thermal conductivity.

Some examples are given below.

(a) High density: adding weight to a part (such as an anchor for a boat), flywheels, counterweights.

(b) Low melting point: Soldering wire, fuse elements (such as in sprinklers to sense fires).

(c) High thermal conductivity: cookware, car radiators, precision instruments that resist thermal warping. The student is encouraged to site other examples.

3.28 Two physical properties that have a major influence on the cracking of workpieces, tools, or dies during thermal cycling are thermal conductivity and thermal expansion. Explain why.

Cracking results from thermal stresses that develop in the part during thermal cycling. Thermal stresses may be caused both by temperature gradients and by anisotropy of thermal expansion. High thermal conductivity allows the heat to be dissipated faster and more evenly throughout the part, thus reducing the temperature gradient. If the thermal expansion is low, the stresses will be lower for a given temperature gradient. When thermal stresses reach a certain level in the part, cracking will occur. If a material has higher ductility, it will be able to undergo more by plastic deformation before possible fracture, and the tendency for cracking will thus decrease.

3.29 Describe the advantages of nanomaterials over traditional materials.

Since nanomaterials have fine structure, they have very high strength, hardness, and strength-to-weight ratios compared to traditional materials. The student is encouraged to review relevant sections in the book; see, for example, pages 125-126, as well as nanoceramics and nanopowders.

3.30 Aluminum has been cited as a possible substitute material for steel in automobiles. What concerns, if any, would you have prior to purchasing an aluminum automobile?

By the student. Some of the main concerns associated with aluminum alloys are that, generally, their toughness is lower than steel alloys; thus, unless the automobile is properly designed and tested, its crashworthiness could suffer. A perceived advantage is that weight savings with aluminum result in higher fuel efficiencies, but steel requires much less energy to produce from ore, so these savings are not as high as initially believed.

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3.31 Lead shot is popular among sportsmen for hunting, but birds commonly ingest the pellets (along with gravel) to help digest food. What substitute materials would you recommend for lead, and why?

Obviously, the humanitarian concern is associated with the waterfowl ingesting lead and, therefore, perishing from lead poisoning; the ideal material would thus be one that is not poisonous. On the other hand, it is important for the shot material to be effective for its purpose, as otherwise a bird is only wounded. Effective shot has a high density, thus a material with a very high density is desired. Referring to Table 3.2 on p. 98, materials with a very high density but greater environmental friendliness are gold and tungsten, but obviously tungsten would be the more logical choice.

3.32 What are metallic glasses? Why is the word "glass" used for these materials?

These materials are described in Section 3.11.9 starting on p. 125. They are produced through such processes as rapid solidification (described in Section 5.10.8 starting on p. 235) so that the material has no grain structure or orientation. Thus, none of the traditional metallic characteristics are present, such as deformation by slip, anisotropy, or grain effects. Because this is very similar to the microstructure and behavior of glass, hence the term.

3.33 Which of the materials described in this chapter has the highest (a) density, (b) electrical conductivity, (c) thermal conductivity, (d) strength, and (e) cost?

As can be seen from Table 3.3 on p. 106, the highest density is for tungsten, and the highest electrical conductivity and thermal conductivity in silver. The highest ultimate strength mentioned in the chapter is for Monel K-500 at 1050 MPa, and the highest cost (which varies from time to time) is usually is associated with superalloys.

3.34 What is twinning? How does it differ from slip?

This is illustrated in Fig. 3.5 on p. 86. In twinning, a grain deforms to produce a mirror-image about a plane of twinning. Slip involves sliding along a plane. An appropriate analogy to differentiate these mechanisms is to suggest that twinning is similar to bending about a plane, and slip is similar to shearing.

Problems

3.35 Calculate the theoretical (a) shear strength and (b) tensile strength for aluminum, plain-carbon steel, and tungsten. Estimate the ratios of their theoretical strength to actual strength.

Equation (3.3) and Eq. (3.5) give the shear and tensile strengths, respectively, as

$$\tau = \frac{G}{2\pi}$$

$$\sigma = \frac{E}{10}$$

The values of E and ν are obtained from Table 2.1 on p. 32, and G is calculated using Eq. (2.24) on p. 49,

$$G = \frac{E}{2(1-\nu)}$$

Thus, the following table can be generated:

Material	E (GPa)	ν	G (GPa)	τ (GPa)	σ (GPa)
Al	79	0.34	60	9.5	7.9
Steel	200	0.33	149	23.7	20
W	400	0.27	274	43.6	40

3.36 A technician determines that the grain size of a certain etched specimen is 6. Upon further checking, it is found that the magnification used was 150, instead of 100 as required by ASTM standards. What is the correct grain size?

To answer this question, one can either interpolate from Table 3.1 on p. 93 or obtain the data for a larger number of grain sizes, as well as the grain diameter as a function of the ASTM No.

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The following data is from the *Metals Handbook*, ASM International:

ASTM No	Grains per mm^2	Grains per mm^3	Avg. grain dia., mm
-3	1	0.7	1.00
-1	4	5.6	0.50
0	8	16	0.35
1	16	45	0.25
2	32	128	0.18
3	64	360	0.125
4	128	1020	0.091
5	256	2900	0.062
6	512	8200	0.044
7	1024	23,000	0.032
8	2048	65,000	0.022

Since the magnification ratio is 150/100=1.5, the diameter was magnified 1.5 times more than it should have been. Thus, the grains appeared larger than they actually are. Because the grain size of 6 has an average diameter of 0.044 mm, the actual diameter is thus

$$d = \frac{0.044 \text{ mm}}{1.5} = 0.0293mm$$

As can be seen from the table, this corresponds to a grain size of about 7.

3.37 Estimate the number of grains in a regular paper clip if its ASTM grain size is 9.

As can be seen in Table 3.1 on p. 93, an ASTM grain size of 9 has 185,000 grains/mm^3. An ordinary paper clip (although they vary depending on the size of paper clip considered) hass a wire diameter of 0.80 mm and a length of 100 mm. Therefore, the paper clip volume is

$$V = \frac{\pi d^2 l}{4} = \frac{\pi(0.80)^2(100)}{4} = 50.5 \text{ mm}^3$$

The number of grains can thus be calculated as (50.5)(185,000)=9.34 million.

3.38 The natural frequency f of a cantilever beam is given by the expression

$$f = 0.56\sqrt{\frac{EIg}{wL^4}},$$

where E is the modulus of elasticity, I is the moment of inertia, g is the gravitational constant, w is the weight of the beam per unit length, and L is the length of the beam. How does the natural frequency of the beam change, if any, as its temperature is increased?

Let's assume that the beam has a square cross section with a side of length h. Note, however, that any cross section will result in the same trends, so students shouldn't be discouraged from considering, for example, circular cross sections. The moment of inertia for a square cross section is

$$I = \frac{h^4}{12}$$

The moment of inertia will increase as temperature increases, because the cross section will become larger due to thermal expansion. The weight per length, w, is given by

$$w = \frac{W}{L}$$

where W is the weight of the beam. Since L increases with increasing temperature, the weight per length will decrease with increasing temperature. Also note that the modulus of elasticity will decrease with increasing temperature (see Fig. 2.9 on p. 41). Consider the ratio of initial frequency (subscript 1) to frequency at elevated temperature (subscript 2):

$$\frac{f_1}{f_2} = \frac{0.56\sqrt{\frac{E_1 I_1 g}{w_1 L_1^4}}}{0.56\sqrt{\frac{E_2 I_2 g}{w_2 L_2^4}}} = \frac{\sqrt{\frac{E_1 I_1}{(W/L_1)L_1^4}}}{\sqrt{\frac{E_2 I_2}{(W/L_2)L_2^4}}} = \frac{\sqrt{\frac{E_1 I_1}{L_1^3}}}{\sqrt{\frac{E_2 I_2}{L_2^3}}}$$

Simplifying further,

$$\frac{f_1}{f_2} = \sqrt{\frac{E_1 I_1 L_2^3}{E_2 I_2 L_1^3}} = \sqrt{\frac{E_1 h_1^4 L_2^3}{E_2 h_2^4 L_a^3}}$$

Letting α be the coefficient of thermal expansion, we can write

$$h_2 = h_1\left(1 + \alpha\Delta T\right)$$

$$L_2 = L_1\left(1 + \alpha\Delta T\right)$$

Therefore, the frequency ratio is

$$\begin{aligned}\frac{f_1}{f_2} &= \sqrt{\frac{E_1 h_1^4 L_2^3}{E_2 h_2^4 L_1^3}} \\ &= \sqrt{\frac{E_1 h_1^4 L_1^3 \left(1+\alpha\Delta T\right)^3}{E_2 h_1^4 \left(1+\alpha\Delta T\right)^4 L_1^3}} \\ &= \sqrt{\frac{E_1}{E_2\left(1+\alpha\Delta T\right)}}\end{aligned}$$

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To compare these effects, consider the case of carbon steel. Figure 2.9 on p. 41 shows a drop in elastic modulus from 190 to 130 GPa over a temperature increase of 1000°C. From Table 3.3 on p. 106, the coefficient of thermal expansion for steel is 14.5 μm/m°C (average of the extreme values given in the table), so that the change in frequency is:

$$\frac{f_1}{f_2} = \sqrt{\frac{E_1}{E_2\,(1+\alpha\Delta T)}}$$

$$= \sqrt{\frac{190}{130\,[1+(14.5\times10^{-6})\,(1000)]}}$$

or $f_1/f_2 = 1.20$. Thus, the natural frequency of the beam decreases when heated. This is a general trend (and not just for carbon steel), namely that the thermal changes in elastic modulus plays a larger role than the thermal expansion of the beam.

3.39 A strip of metal is reduced in thickness by cold working from 25 mm to 15 mm. A similar strip is reduced from 25 mm to 10 mm. Which one of these strips will recrystallize at a lower temperature? Why?

In the first case, reducing the strip from 25 to 15 mm involves a true strain (absolute value) of

$$\epsilon = \ln\left(\frac{25}{15}\right) = 0.511$$

and for the second case,

$$\epsilon = \ln\left(\frac{25}{10}\right) = 0.916$$

A review of Fig. 3.18 will indicate that, because of the higher degree of cold work and hence higher stored energy, the second case will involve recrystallization at a lower temperature than the first case.

3.40 A 1-m long, simply-supported beam with a round cross section is subjected to a load of 50 kg at its center. (a) If the shaft is made from AISI 303 steel and has a diameter of 20 mm, what is the deflection under the load? (b) For shafts made from 2024-T4 aluminum, architectural bronze, and 99.5% titanium, respectively, what must the diameter of the shaft be for the shaft to have the same deflection as in part (a)?

(a) For a simply-supported beam, the deflection can be obtained from any solid mechanics book as

$$\delta = \frac{PL^3}{48EI}$$

For a round cross section with diameter of 20 mm, the moment of inertia is

$$I = \frac{\pi d^4}{64} = \frac{\pi(0.020)^4}{64} = 7.85\times10^{-9}\ \text{m}^4$$

From Table 2.1, E for steel is around 200 GPa. The load is 50 kg or 490 N; therefore, the deflection is

$$\delta = \frac{PL^3}{48EI} = \frac{(490\ \text{N})(1\ \text{m})^3}{48(200\ \text{GPa})(7.85\times10^{-9}\ \text{m}^4)}$$

or $\delta = 0.00650$ m $= 6.5$ mm.

(b) It is useful to express the diameter as a function of deflection:

$$\delta = \frac{PL^3}{48EI} = \frac{64PL^3}{48\pi Ed^4}$$

Solving for d, we have

$$d = \left(\frac{4PL^3}{3\pi E\delta}\right)^{1/4}$$

Thus, the following table can be constructed, with the elastic moduli taken from Table 2.1 on p. 32.

Material	E (GPa)	d (mm)
2024-T4 Al	79	25.2
Arch. bronze	110	23.2
99.5% Ti	80	25.1

3.41 If the diameter of the aluminum atom is 0.5 nm, estimate the number of atoms in a grain with an ASTM size of 5.

If the grain size is 5, there are 2900 grains per mm^3 of aluminum, and each grain has a volume of $1/2900 = 3.45\times10^{-4}$ mm^3. Recall that for an fcc material there are four atoms per unit cell, with a total volume of $16\pi R^3/3$, and that the diagonal, a, of the unit cell is given by

$$a = \left(2\sqrt{2}\right)R$$

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Hence,

$$\text{APF}_{\text{fcc}} = \frac{(16\pi R^3/3)}{(2R\sqrt{2})^3} = 0.74$$

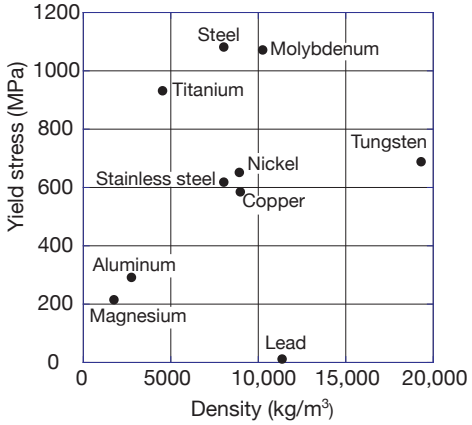
Note that as long as all the atoms in the unit cell are of the same size, the atomic packing factors do not depend on the atomic radius. Therefore, the volume of the grain taken up by atoms is $(3.45\times10^{-4})(0.74) = 2.55\times10^{-4}$ mm^3. (Recall that 1 mm=10^6 nm.) The diameter of an aluminum atom is 0.5 nm, thus its radius is 0.25 nm or 0.25×10^{-6} mm. The volume of an aluminum atom is

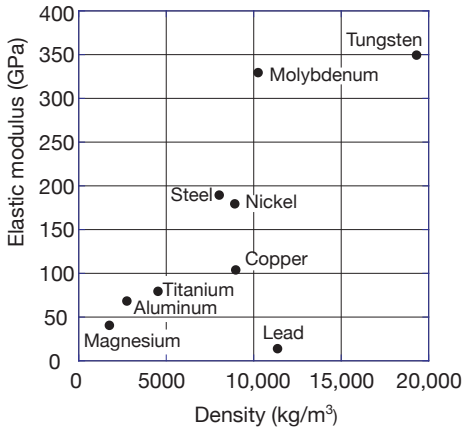
$$V = \frac{4\pi R^3}{3} = \frac{4\pi(0.25 \times 10^{-6})^3}{3}$$

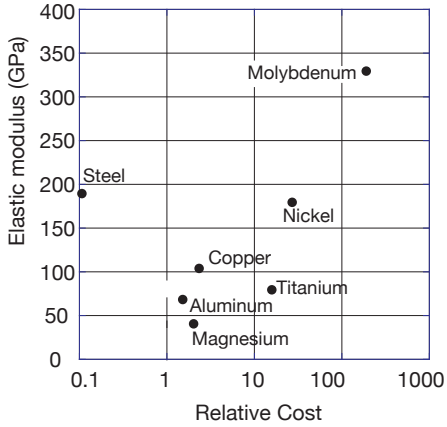
or 6.54×10^{-20} mm^3. Dividing the volume of aluminum in the grain by the volume of an aluminum atom gives the total number of atoms in the grain as $(2.55 \times 10^{-4})/(6.54 \times 10^{-20}) = 3.90 \times 10^{15}$.

3.42 Plot the following for the materials described in this chapter: (a) yield stress versus density, (b) modulus of elasticity versus strength, and (c) modulus of elasticity versus relative cost. *Hint:* See Table 16.4.

The plots are shown below, based on the data given in Tables 2.1 on p. 32, 3.3 on p. 106, and 16.4 on p. 971. Average values have been used to obtain these plots.







3.43 The following data is obtained in tension tests of brass:

Grain Size (μm)	Yield stress (MPa)
15	150
20	140
50	105
75	90
100	75

Does this material follow the Hall-Petch effect? If so, what is the value of k?

First, it is obvious from this table that the material becomes stronger as the grain size decreases, which is the expected result. However, it is not clear whether Eq. (3.8) on p. 92 is applicable. It is possible to plot the yield stress as a function of grain diameter, but it is better to plot it as a function of $d^{-1/2}$, as follows:

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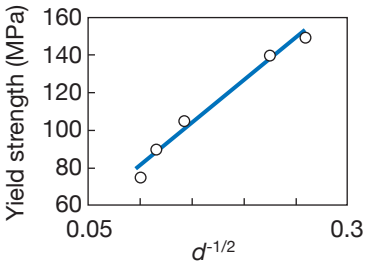


The least-squares curve fit for a straight line is

$$Y = 35.22 + 458d^{-1/2}$$

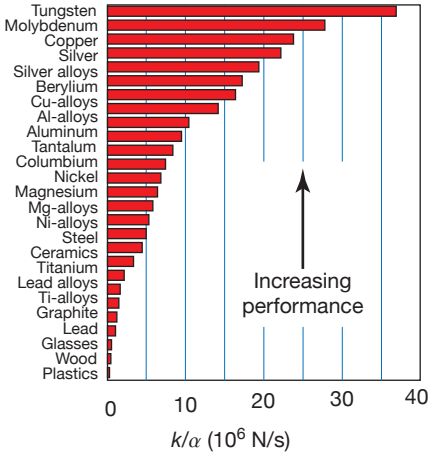
with an R factor of 0.990. This suggests that a linear curve fit is proper, and it can be concluded that the material does follow the Hall-Petch effect, with a value of $k = 458$ MPa-$\sqrt{\mu m}$.

3.44 It can be shown that thermal distortion in precision devices is low for high values of thermal conductivity divided by the thermal expansion coefficient. Rank the materials in Table 3.3 according to their suitability to resist thermal distortion.

The following table can be compiled, using maximum values of thermal conductivity and minimum values of thermal expansion coefficient (to show optimum behavior for low thermal distortion):

Material	k	α	k/α
Plastics	0.4	72	0.00556
Wood	0.4	2.	0.20
Glasses	1.7	4.6	0.37
Lead	35.	29.4	1.19
Graphite	10.	7.86	1.27
Ti alloys	12.	8.1	1.48
Pb alloys	46	27.1	1.70
Ti	17.	8.35	2.04
Ceramics	17.	5.5	3.09
Steels	52	11.7	4.44
Ni alloys	63	12.7	4.96
Mg alloys	138	26	5.31
Mg	154.	26	5.92
Iron	74.	11.5	6.43
Nickel	92	13.3	6.91
Columbium	52	7.1	7.3
Tantalum	54	6.5	8.30
Aluminum	222	23.6	9.40
Al Alloys	239	23	10.3
Cu alloys	234	16.5	14.18
Gold	317.	19.3	16.4
Berylium	146	8.5	17.1
Si	148.	7.63	19.3
Silver	429	19.3	22.2
Copper	393	16.5	23.8
Molybdenum	142	5.1	27.8
Tungsten	166.	4.5	36.9

This data is shown graphically as follows:



3.45 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

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Chapter 4

Surfaces, Tribology, Dimensional Characteristics, Inspection, and Product Quality Assurance

Questions

4.1 Explain what is meant by surface integrity. Why should we be interested in it?

Whereas surface roughness describes the geometric features of a surface, surface integrity consists of not only the geometric description but also the mechanical and metallurgical properties and characteristics. As described in Section 4.2 starting on p. 132, surface integrity has a major effect on properties, such as fatigue strength and resistance to corrosion, and hence the service life of a product.

4.2 Why are surface-roughness design requirements in engineering so broad? Give appropriate examples.

As described in Section 4.3 starting on p. 134, surface-roughness design requirements for typical engineering applications can vary by as much as two orders of magnitude for different parts. The reasons and considerations for this wide range include the following:

(a) Precision required on mating surfaces, such as seals, gaskets, fittings, and tools and dies. For example, ball bearings and gages require very smooth surfaces, whereas surfaces for gaskets and brake drums can be quite rough.

(b) Tribological considerations, that is, the effect of surface roughness on friction, wear, and lubrication.

(c) Fatigue and notch sensitivity, because rougher surfaces generally have shorter fatigue lives.

(d) Electrical and thermal contact resistance, because the rougher the surface, the higher the resistance will be.

(e) Corrosion resistance, because the rougher the surface, the more the possibility that corrosive media may be entrapped.

(f) Subsequent processing, such as painting and coating, in which a certain degree of roughness can result in better bonding.

(g) Appearance, because, depending on the application, a rough or smooth surface may be preferred.

(h) Cost considerations, because the finer the finish, the higher is the cost.

4.3 We have seen that a surface has various layers. Describe the factors that influence the thickness of each of these layers.

These layers generally consist of a work-hardened layer, oxides, adsorbed gases, and various contaminants (see Fig. 4.1 on p. 132). The

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thickness of these layers is influenced by the nature of surface-generation process employed (casting, forming, machining, grinding, polishing, etc.) and the environment to which the surface is exposed during and after its generation. Thus, for example, dull cutting tools or severe surface deformation during metalworking operations produce a relatively thick work-hardened layer. In addition to production methods and choice of processing parameters, an equally important factor is the effect of the environment and temperature on the workpiece material.

4.4 What is the consequence of oxides of metals being generally much harder than the base metal? Explain.

The consequences are numerous, and the oxide can be beneficial as well as detrimental. In sliding contact, the oxide is a hard surface that, as a result, is wear resistant [see Eq. (4.6) on p. 145], and it can also protect the substrate from further chemical attack. However, if an oxide wear particle spalls from the surface, a detrimental three-body wear situation can result. Also, as discussed in Chapter 2, the hard surface layers may be detrimental from a fatigue standpoint if their ductility is compromised. Finally, if a material is plastically deformed, as in the processes described in Chapters 6 and 7, the oxide layer may crack or even break off, resulting in a surface finish that may be unacceptable for the particular application.

4.5 What factors would you consider in specifying the lay of a surface?

Specifying the lay of a surface requires considerations such as the nature of the mating surfaces and their application, direction of relative sliding, frictional effects, lubricant entrapment, and optical factors such as appearance and reflectivity of the surface. Physical properties such as thermal and electrical conductivity may also be significant.

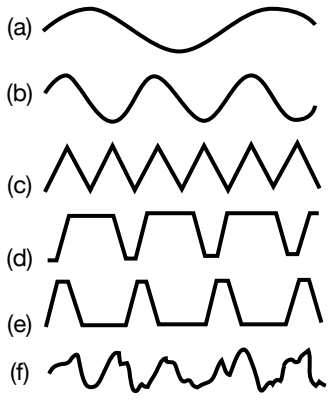
4.6 Describe the effects of various surface defects (see Section 4.3 starting on p. 134) on the performance of engineering components in service. How would you go about determining whether or not each of these defects is important for a particular application?

Surface defects can have several effects on the performance of engineering components in service. Among these effects are premature failure under various types of loading, crevice corrosion, adverse effects on lubrication, and whether the components will function smoothly or there will be vibration or chatter.

The manner in which their importance for a particular operation can be assessed is by observing the defect type and its geometry, and how these defects would relate to component performance. The direction and depth of a crack, for example, should be reviewed with respect to the direction of tensile stresses or direction of relative movement between the surfaces. Another example is the possibility of crevice corrosion in the presence of a hostile environment.

4.7 Explain why the same surface roughness values do not necessarily represent the same type of surface.

As can be seen in Eqs. (4.1) and (4.2) on p. 134, there is an infinite range of values for a, b, c, d, etc. that would give the same arithmetic mean value R_a or the root-mean-square average value R_q. This can be seen graphically, as the surfaces shown below are examples that result in the same R_a values but are very different geometrically and have different tribological performance (from Bhushan, B., *Introduction to Tribology*, Wiley, 2002).



4.8 In using a surface-roughness measuring instrument, how would you go about determining the cutoff value? Give appropriate examples.

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The determination depends on various factors. For example, if waviness is repeatable, the cutoff need not be longer than the waviness cycle. Also, if there is poor control of processing parameters during manufacturing, such that the surface produced is highly irregular, then cutoff should be long enough to give a representative roughness value. If the quality of the workpiece material is poor, with numerous flaws, inclusions, impurities, etc., the cutoff must be long enough to be representative of the surface in general. The lay could also play a significant role in cutoff selection. The cutoff should be related to the spacing of asperities, which has been found to be about an order of magnitude larger than the roughness for most surfaces. Thus, several recommendations can be found in the technical literature for different methods of surface preparation. For example, the following data is recommended by a profilometer manufacturer:

R_a (μm)	Cut-off length mm
0.025	0.08
0.05	0.25
0.1	0.25
0.2	0.25
0.4	0.25
0.8	0.8
1.6	0.8
3.2	2.5
6.3	2.5
12.5	2.5

4.9 What is the significance of the fact that the stylus path and the actual surface profile generally are not the same?

This situation indicates that profilometer traces are not exact duplicates of actual surfaces and that such readings can be misleading for precise study of surfaces. (Note, however, that the roughness in Fig. 4.4 on p. 137 is highly exaggerated because of the differences between the horizontal and vertical scales.) For example, surfaces with deep narrow valleys will be measured smoother than they really are. This can have significant effects on the estimating the fatigue life, corrosion, and proper assessment of the capabilities of various manufacturing processes.

4.10 Give two examples each in which waviness of a surface would be (1) desirable and (2) undesirable.

Suggested examples are, for desirable: suggested examples are aesthetic reasons, appearance, beneficial effects of trapping lubricants between two surfaces. For undesirable: unevenness between mating surfaces, difficulty of providing a tight seal, sliding is not smooth. The student is encouraged to give other examples.

4.11 Explain why surface temperature increases when two bodies are rubbed against each other. What is the significance of temperature rise due to friction?

This topic is described in Section 4.4.1 starting on p. 138. When bodies rub against each other, friction causes energy dissipation which is in the form of heat generation at the surfaces. If the rubbing speed is very slow, and the thermal conductivity of the workpiece is very high, then the temperature rise may be negligible. More commonly, there can be a major temperature rise at the surface. The significance of this temperature rise is that surfaces may be more chemically active or may be develop higher thermal stresses and possibly result in heat checking. Note that this is not necessarily detrimental because chemical reactivity is required for many boundary and extreme-pressure lubricants to bond to a surface.

4.12 To what factors would you attribute the fact that the coefficient of friction in hot working is higher than in cold working, as shown in Table 4.1?

The factors that have a significant influence on friction are described in Section 4.4.1 starting on p. 138. For hot working, specifically, important factors are the tendency for increased junction strength (due to greater affinity), oxide formation, strength of oxide layers, and the effectiveness of lubricants at elevated temperatures.

4.13 In Section 4.4.1, we note that the values of the coefficient of friction can be much higher than unity. Explain why.

This phenomenon is largely a matter of definition of the coefficient of friction μ, and also

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indicates the desirable feature of the concept of friction factor, m, which can range between 0 and 1; see Eq. (4.5) on p. 140. Consider, for example, Eq. (4.3) on p. 139. If, for a variety of reasons, the mating surfaces have developed extensive microwelds during sliding, then the load is removed and the two surfaces are allowed to slide against each other, there would be considerable friction force, F, required. Since for this case the load N is now negligible, the coefficient of friction, $\mu = F/N$, would indeed be very high. This can also be seen if the mating surfaces consisted of adhesive tape or Velcro®.

4.14 Describe the tribological differences between ordinary machine elements (such as meshing gears, cams in contact with followers, and ball bearings with inner and outer races) and elements of metalworking processes (such as forging, rolling, and extrusion, which involve workpieces in contact with tools and dies).

The tribological differences are due to significant differences in parameters such as contact loads and stresses, relative speeds between sliding members, workpiece temperatures, temperature rise during application, types of materials involved, types of lubricants used, and the particular environment. Also, referring to Fig. 4.6 on p. 140, note that the manufacturing processes all take place at very high normal stresses and as a result, non-linear relationships between friction and normal force are uncommon. With machine elements such as gears, cams, and bearings, however, normal forces are not as high, and a Coulomb friction law as stated in Eq. (4.3) on p. 139 generally applies. Students are encouraged to develop a list with several specific examples.

4.15 Give the reasons that an originally round specimen in a ring-compression test may become oval after deformation.

The specimen may flow more easily in one direction than another for reasons such as:

(a) anisotropy of the workpiece material,

(b) the lay of the specimen surfaces, thus affecting frictional characteristics,

(c) the lay on the surface of the flat dies employed,

(d) uneven lubricant layer over the mating surfaces, and

(e) lack of symmetry of the test setup, such as platens that are not parallel.

4.16 Can the temperature rise at a sliding interface exceed the melting point of the metals? Explain.

When the heat generated due to friction and that due to work of plastic deformation exceeds the rate of heat dissipation from the surfaces through conduction and convection, the surfaces will soften and even melt, and the heat input will be dissipated as heat of fusion necessary for changing from a solid to a liquid phase. This heat represents a high amount of energy, thus the surface temperature will not exceed the melting point.

4.17 List and briefly describe the types of wear encountered in engineering practice.

This topic is discussed in Section 4.4.2 on p. 144. Basically, the types of wear are:

- Adhesive wear, where material transfer occurs because one material has bonded to the other and relative motion shears the softer material; see Fig. 4.10 on p. 145.
- Abrasive wear, where a hard asperity plows into a softer material, producing a chip, as shown in Fig. 4.10 on p. 145. This can be a two-body or a three-body phenomenon.
- Corrosive wear, which occurs when chemical or electrochemical reactions take place, thereby removing material from surfaces.
- Fatigue wear, common in bearings and gears, is due to damage associated with cyclic loading, where cracks propagate and cause material loss through spalling.
- Erosion, caused by the abrasive action of loose hard particles.
- Impact wear, refers to spalling associated with dynamic loading of a surface.

4.18 Explain why each of the terms in the Archard formula for adhesive wear, Eq. (4.6) on p. 145, should affect the wear volume.

The following observations can be made regarding this formula:

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(a) The wear coefficient, k, indicates the affinity of the two contacting surfaces to develop microwelds, as shown in Table 4.2 on p. 146. The greater the affinity, the greater the probability of forming strong microwelds, hence the higher the adhesive wear.

(b) The greater the distance traveled, L, obviously the higher the amount of wear.

(c) The greater the normal load, W, the greater the tendency to form strong microwelds, hence the greater the wear.

(d) The higher the hardness of the softer body, the lower the possibility of forming strong junctions at the interface, hence the lower the wear. Note also the significant effect of lubrication on the magnitude of k, as to be expected.

4.19 How can adhesive wear be reduced? How can fatigue wear be reduced?

Adhesive wear can be reduced by studying the effects outlined in the answer to Problem 4.18 above. Fatigue wear can be reduced by:

(a) reducing the load and sliding distance and increasing the hardness, consistent with Problem 4.18 above;

(b) improving the quality of the contacting materials, such as eliminating inclusions, impurities, and voids;

(c) improving the surface finish and integrity during the manufacturing process;

(d) surface working, such as shot peening or other treatments;

(e) reducing contact stresses; and

(f) reducing the number of total cycles. (See also Section 2.7 starting on p. 56.)

4.20 It has been stated that as the normal load decreases, abrasive wear is reduced. Explain why this is so.

For abrasive wear to occur, the harder or rougher surface must penetrate the softer surface to some depth. Thus, this phenomenon becomes similar to a hardness test, whereby the harder the surface, the less the penetration of the indenter. Consequently, as the normal load decreases, the surfaces do not penetrate as much and, hence, the groove produced (by an abrasive particle sliding against a surface) is more shallow, thus abrasive wear is lower.

4.21 Does the presence of a lubricant affect abrasive wear? Explain.

Although it is not readily apparent from Eq. (4.6) on p. 145, the presence of a lubricant can affect abrasive wear by virtue of the fact that a lubricant can have some effect (although to a very minor extent) on the depth of penetration, as well as the manner in which the slivers are produced and their dimensions (as described in Chapter 8). It should also be noted that the presence of a lubricant will cause the wear particles to stick to the surfaces, thus interfering with the operation. This topic has not been studied to any extent, thus it would be suitable for literature search on the part of students.

4.22 Explain how you would estimate the magnitude of the wear coefficient for a pencil writing on paper.

Referring to Eq. (4.6) on p. 145, since the wear volume, the force on the pencil, and the sliding distance can be determined, we can then calculate the dimensionless wear coefficient, k/H. The hardness of the pencil material can be measured through a microhardness test. The tribology of pencil on paper is an interesting area for inexpensive experimentation. Note also that different types of paper will result in different wear coefficients as well (e.g., rough construction paper vs. writing paper vs. newspaper, or even wax paper). This topic can easily be expanded into a design project to encourage students to develop wear tests to determine k.

4.23 Describe a test method for determining the wear coefficient k in Eq. (4.6). What would be the difficulties in applying the results from this test to a manufacturing application, such as predicting the life of tools and dies?

Several tests have been developed for evaluating wear coefficients, and this topic would be suitable as a student project. The following are among the more commonly used:

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- The pin-on-disk test uses a pin sliding over a rotating disk; wear volume is obtained from the change in the length and geometry of the pin or by using profilometry on the disk.
- The pin-on-flat test uses a pin that reciprocates against a flat surface.
- A ring test uses rotating rings and is especially used to evaluate fatigue wear.
- An abrasive wear test that is commonly performed uses a rubber wheel to press loose abrasives against a workpiece.

All of these tests have significant drawbacks when applied to manufacturing processes. Most importantly, it is difficult to reproduce the contact stresses encountered in a manufacturing environment, such as temperature and strain rate), which will then have a major effect on wear. Furthermore, there is a need to maintain the same surface condition as encountered in manufacturing operations.

4.24 Why is the abrasive wear resistance of a material a function of its hardness?

Higher hardness indicates greater resistance to penetration, hence less penetration of the abrasive particles or hard protrusions into surfaces, and the grooves produced are not as deep. Thus, abrasive wear is a function of hardness.

4.25 We have seen that wear can have detrimental effects on engineering components, tools, dies, etc. Can you visualize situations in which wear could be beneficial? Give some examples. (*Hint:* Note that writing with a pencil is a wear process.)

Consider, for example:

(a) running-in periods of machinery,

(b) burnishing, involving improvements in surface finish and appearance due to a small amount of controlled wear.

(c) using sandpaper to remove splinters from wood,

(d) using a scouring pad on cookware to remove dried or burnt food particles.

(e) grinding and other manufacturing operations, as described in Chapter 9, where fine tolerances and good surface finishes are achieved through basically controlled wear mechanisms.

The student is encouraged to think of more examples.

4.26 On the basis of the topics discussed in this chapter, do you think there is a direct correlation between friction and wear of materials? Explain.

The answer is no, not directly. Consider, for example, the fact that ball and roller bearings have very low friction yet they do undergo wear, especially by surface fatigue. Also, ceramics have low wear rate, yet they can have significant frictional resistance. The following data, obtained from J. Halling, *Principles of Tribology*, 1975, p. 9, clearly demonstrates that high friction does not necessarily correspond to high wear:

Materials	μ	Wear rate ($cm^3/cm \times 10^{-12}$)
Mild steel on mild steel	0.62	157,000
60/40 leaded brass	0.24	24,000
PTFE	0.18	2000
Stellite	0.60	310
Ferritic stainless steel	0.53	270
Polyethylene	0.65	30
Tungsten carbide on itself	0.35	2

4.27 You have undoubtedly replaced parts in various appliances and automobiles because they were worn. Describe the methodology you would follow in determining the type(s) of wear these components have undergone.

This is an open-ended problem, and the student should be asked to develop a methodology based on Section 4.4.2 starting on p. 144. The methodology should include inspection at a number of levels, for example, visual determination of the surface, as well as under a light microscope and scanning electron microscope. Surface scratches, for instance, are indicative of abrasive wear; spalling would suggest fatigue wear; and a burnished surface suggests adhesive wear. The wear particles must also be investigated. If the particles have a bulky form, they are likely to be adhesive wear particles, including surface oxides. Flakes are indicative of adhesive wear of metals that do not have an oxide

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surface. Abrasive wear results in slivers or wear particles with a larger aspect ratios.

4.28 Why is the study of lubrication regimes important?

The reason is primarily due to the fact that each regime, ranging from full-fluid film to sliding of dry surfaces, has its own set of variables that affect performance, load-bearing capacity, friction, wear, temperature rise, and surface damage. Consequently, in the event of poor performance, one should concentrate and further investigate those particular parameters. Also, the lubricant film plays a major role in the ultimate workpiece surface roughness that is produced. The student may elaborate further, based on the topics covered in Section 4.4.3 starting on p. 149.

4.29 Explain why so many different types of metalworking fluids have been developed.

The student may discuss this topic, based on various topics listed in Section 4.4.4 starting on p. 151; thus, for example, end result expected (to reduce friction or wear), the particular manufacturing process employed, the materials used, the temperatures that will be encountered, costs involved, etc.

4.30 Differentiate between (1) coolants and lubricants, (2) liquid and solid lubricants, (3) direct and indirect emulsions, and (4) plain and compounded oils.

The answers can be found in Section 4.4.4 starting on p. 151. Basically,

(a) a coolant is mainly intended to remove heat, whereas a lubricant has friction and wear reduction functions as well. For example, water is an excellent coolant but is a poor lubricant (unless used in hydrodynamic lubrication), whereas water-soluble oils generally serve both functions.

(b) The difference between liquid and solid lubricants is that they have different phases. However, although solid lubricants are solid at room temperature, they may not be so at operating temperatures.

(c) Direct emulsions have oil suspended in water; indirect (invert) emulsions have water droplets suspended in oil.

(d) Plain oils contain the base oil only, whereas compounded oils have various additives in the base oil to fulfill special criteria such as lubricity and workpiece surface brightening.

4.31 Explain the role of conversion coatings. Based on Fig. 4.13, what lubrication regime is most suitable for application of conversion coatings?

Conversion coatings provide a rough and porous surface on workpieces. The porosity is infiltrated by the lubricant, thus aiding in entrainment and retention of the lubricant in the metalworking process. Considering the regimes of lubrication, it is clear that conversion coatings are not useful in full-film lubrication, since a thick lubricant film already exits at the interfaces without the need for a rough surface. It is, however, beneficial for boundary or mixed-lubrication regimes.

4.32 Explain why surface treatment of manufactured products may be necessary. Give several examples.

This topic is described at the beginning of Section 4.5 on p. 154. Examples are:

- Some surfaces may be coated with a hard material for wear resistance, such as ceramic-coated cutting or forming tools.
- Jewelry and tableware are electroplated with gold or silver, for aesthetic and some functional reasons.
- Bolts, nuts, and other fasteners are zinc coated for corrosion resistance.
- Some automotive parts are plated with decorative chrome (although not used as often now) for aesthetic reasons.

The student is encouraged to develop additional specific applications, based on the materials covered in this section of the text.

4.33 Which surface treatments are functional, and which are decorative? Give several examples.

A review of the processes described indicates that most surface treatments are functional. A few, such as electroplating, anodizing, porcelain enameling, and ceramic coating, are generally regarded as both functional and decorative.

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The students are encouraged to give specific examples from their personal experience and observations.

4.34 Give examples of several typical applications of mechanical surface treatment.

The applications are described in Section 4.5.1 starting on p. 154. Some examples are:

- The shoulders of shafts can be roller burnished to impart a compressive residual stress and thus improve fatigue life.
- Crankshafts, rotors, cams, and other similar parts are shot peened in order to increase surface hardness and wear resistance, as well as improve fatigue life.
- Railroad rails can be hardened by explosive hardening.

The student is encouraged to give additional examples.

4.35 Explain the difference between case hardening and hard facing.

Case hardening is a heat treatment process (described in Section 5.11.3 on p. 241) performed on a manufactured part; hard facing involves depositing metal on a surface using various techniques described in the text.

4.36 List several applications for coated sheet metal, including galvanized steel.

There are numerous applications, ranging from galvanized sheet-steel car bodies for corrosion protection, to sheet-metal television cabinets, office equipment, appliances, and gutters and down spouts. Polymer-coated steels are typically used for food and beverage containers and also for some sheet-metal parts. The student is encouraged to develop lists for specific applications.

4.37 Explain how roller-burnishing processes induce residual stresses on the surface of workpieces.

Roller burnishing, like shot peening, induces residual surface compressive stresses due to localized plastic deformation of the surface. These stresses develop because the surface layer tends to expand during burnishing, but the bulk prevents these layers from expanding laterally freely. Consequently, compressive residual stresses develop on the surface.

4.38 List several products or components that could not be made properly, or function effectively in service, without implementation of the knowledge involved in Sections 4.2 through 4.5.

This is an open-ended problem that can be answered in many ways. Some examples of components that require the knowledge in Sections 4.2 through 4.5 include:

- Brake drums, rotors, and shoes could not be designed properly without an understanding of friction and wear phenomena.
- Crankshaft main bearings and piston bearings require an understanding of lubrication.
- A wide variety of parts have functional coatings, such as galvanized sheet metal for automotive body panels, zinc coatings on bolts and nuts, and hard chrome coatings for wear resistance, and cutting tools can have nitride coatings through chemical vapor deposition.
- Aircraft fuselage components have a strict surface roughness requirement.

4.39 Explain the difference between direct- and indirect-reading linear measurements.

In direct reading, the measurements are obtained directly from numbers on the measuring instruments, such as a rule, vernier caliper, or micrometer. In indirect reading, the measurements are made using calipers, dividers, and telescoping gages. These instruments do not have numbers on them and their setting is measured subsequently using a direct-measuring instrument.

4.40 Why have coordinate-measuring machines become important instruments in modern manufacturing? Give some examples of applications.

These machines are built rigidly and are very precise, and are equipped with digital readouts and also can be linked to computers for on-line inspection of parts. They can be placed close to machine tools for efficient inspection and rapid

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feedback for correction of processing parameters before the next part is made. They are also being made more rugged to resist environmental effects in manufacturing plants, such as temperature variations, vibration, and dirt.

4.41 Give reasons why the control of dimensional tolerances in manufacturing is important.

This topic is described in Section 4.7 starting on p. 170. Generally, for instance, products perform best when they are at their design specification, so dimensional tolerances should be controlled to obtain as good of performance as is possible. The student is encouraged to give several examples.

4.42 Give examples where it may be preferable to specify unilateral tolerances as opposed to bilateral tolerances in design.

By the student. For example, when a shrink fit is required, it may be beneficial to specify a shaft and hole tolerance with a unilateral tolerance, so that a minimum contact pressure is assured.

4.43 Explain why a measuring instrument may not have sufficient precision.

A caliper, for example, that can only measure to the nearest 0.001 in. is not precise enough to measure a 0.0005 in. press-fit clearance between two mating gears.

4.44 Comment on the differences, if any, between (1) roundness and circularity, (2) roundness and eccentricity, and (3) roundness and cylindricity.

(a) The terms roundness and circularity are usually interchangeable, with the term out of roundness being commonly used. Circularity is defined as the condition of a surface of revolution where all points of the surface intersected by any plane perpendicular to an axis or passing through a center are equidistant from the center. Also, we usually refer to a round shaft as being round, whereas there are components and parts in which only a portion of a surface is circular. (See, for example, circular interpolation in numerical control, described in Fig. 14.11c on p. 882).

(b) Eccentricity may be defined as not having the same center, or referring to concentricity in which two or more features have a common axis. Thus, a round shaft may be mounted on a lathe at its ends in such a manner that its rotation is eccentric.

(c) Cylindricity is defined similarly to circularity, as the condition of a surface of revolution in which all points of the surface are equidistant from a common axis. A straight shaft with the same roundness along its axis would possess cylindricity; however, in a certain component, roundness may be confined to only certain narrow regions along the shaft, thus it does not have cylindricity over its total length.

4.45 It has been stated that dimensional tolerances for nonmetallic stock, such as plastics, are usually wider than for metals. Explain why. Consider physical and mechanical properties of the materials involved.

Nonmetallic parts have wider tolerances because they often have low elastic modulus and strength, are soft, have high thermal expansion, and are therefore difficult to manufacture with high accuracy. (See also Chapter 10).

4.46 Describe the basic features of nondestructive testing techniques that use electrical energy.

Nondestructive testing techniques that use electrical energy are magnetic particle, ultrasonic, acoustic emission, radiography, eddy current, and holography. Their basic features are described in Section 4.8.1.

4.47 Identify the nondestructive techniques that are capable of detecting internal flaws and those that only detect external flaws.

Internal flaws: ultrasonic, acoustic emission, radiography, and thermal. External flaws: liquid penetrants, magnetic particle, eddy current, and holography. Some of these techniques can be utilized for both types of defects.

4.48 Which of the nondestructive inspection techniques are suitable for nonmetallic materials? Why?

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By the student. Since nonmetallic materials are characterized by lack of electrical conductivity, techniques such as magnetic particle and eddy current would not be suitable.

4.49 Why is automated inspection becoming an important aspect of manufacturing engineering?

As described throughout the text, almost all manufacturing equipment is now automated (see also Chapters 14 and 15). Consequently, inspection at various stages of production should also be automated in order to improve productivity, by keeping the flow of materials and products at an even, rapid pace.

4.50 Describe situations in which the use of destructive testing techniques is unavoidable.

Destructive testing techniques will be necessary for determining, for example, the mechanical properties of products being made, because nondestructive techniques generally cannot do so. Such property determination requires test samples (as described throughout Chapter 2), such as from different regions of a forging or a casting, before proceeding with large-scale production of the product. This approach is particularly important for parts that are critical, such as jet-engine turbine components and medical implants.

4.51 Should products be designed and built for a certain expected life? Explain.

Product life cycle and cradle-to-cradle design are discussed in Section 16.4. The students are encouraged to review this material, as well as describe their own thoughts and cite their experiences with purchasing various products. This is an important topic, and includes several technical as well as economic considerations and personal choices.

4.52 What are the consequences of setting lower and upper specifications closer to the peak of the curve in Fig. 4.23?

In statistical process control, setting the specifications closer to the center of the distribution will cause more of the sample points to fall outside the limits, as can be seen in Fig. 4.21c on p. 177, thus increasing the rejection rate.

4.53 Identify factors that can cause a process to become out of control. Give several examples of such factors.

This situation can occur because of various factors, such as:

(a) the gradual deterioration of coolant or lubricant,

(b) debris interfering with the manufacturing operation,

(c) an increase or decrease in the temperature in a heat-treating operation,

(d) a change in the properties of the incoming raw materials, and

(e) a change in the environmental conditions, such as temperature, humidity, and air quality.

The student is encouraged to give other examples.

4.54 In reading this chapter, you will have noted that the specific term *dimensional tolerance* is often used, rather than just the word *tolerance*. Do you think this distinction is important? Explain.

As a general term, tolerances relate not only to dimensions but to parameters such as the mechanical, physical, and chemical properties of materials, including their compositions. For example, in the electronics industry, there are tolerances with respect to part dimensions, but also with respect to electrical properties. In most mechanical engineering design applications, however, the distinction is not significant.

4.55 Give an example of an assignable variation and a chance variation.

This topic is defined and described in Section 4.9.1 starting on p. 176, with an example on bending of beams to determine their strength. The students are encouraged to describe an example of their own.

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Problems

4.56 Referring to the surface profile in Fig. 4.3, give some numerical values for the vertical distances from the center line. Calculate the R_a and R_q values. Then give another set of values for the same general profile, and calculate the same quantities. Comment on your results.

As an example, two students took the same figure and enlarged it, one with a copy machine, the other by scanning it into a computer and zooming in on the figure. The first student printed the figure on graph paper and interpolated numbers for points a through l. The second sketched a grid over the drawing and interpolated numbers as well. Their results are given as:

Point	Student 1	Student 2	Modified 2
a	3.8	5.0	3.79
b	2.5	3.0	2.27
c	4.0	5.5	4.17
d	5.5	7.5	5.69
e	2.0	2.5	1.90
f	-3.5	-4.5	-3.41
g	-5.0	-6.5	-4.93
h	-4.0	-5.5	-4.17
i	-4.0	-5.0	-3.79
j	-5.5	-7.0	-5.31
k	-3.5	-4.5	-3.41
l	-1.0	-1.0	-0.76

Note that the scales are slightly off, due to the fact that the grids used were different. To have the same peak-to-peak value as Student 1, the values of Student 2 were scaled as in the Modified 2 column. The R_a and R_q values, as calculated from Eqs. (4.1) and (4.2) on p. 134, are:

Source	R_a	R_q
Student 1	3.69	5.45
Student 2	4.79	5.12
Modified 2	3.63	3.88

Note that the roughness values depend on the scales used for the plots. When normalized linearly, so that the data has the same peak-to-peak value, the R_a roughnesses match very well. However, the R_q roughness values do not match well; a second-order mapping of data points would improve the performance, however.

4.57 Calculate the ratio of R_a/R_q for (a) a sine wave, (b) a saw-tooth profile, (c) a square wave.

This solution uses the continuous forms of roughness given by Eqs. (4.1) and (4.2) on p. 134.

(a) The equation of a sine wave with amplitude a is

$$y = a \sin \frac{2\pi x}{l}$$

Thus, Eq. (4.1) gives

$$R_a = \frac{1}{l}\int_0^l \left| a \sin \frac{2\pi x}{l} \right| dx = \frac{2a}{l}\int_0^{l/2} \sin \frac{2\pi x}{l} dx$$

Integrating,

$$\begin{aligned} R_a &= -\frac{2a}{l}\frac{l}{2\pi}\left(\cos \frac{2\pi x}{l}\right)_0^{l/2} \\ &= -\frac{a}{\pi}(\cos\pi - \cos 0) = -\frac{a}{\pi}(-1-1) \\ &= \frac{2a}{\pi} \end{aligned}$$

To evaluate R_q for a sine wave, recall that

$$\int \sin^2 u \, du = \frac{u}{2} - \frac{1}{4}\sin 2u$$

which can be obtained from any calculus book or table of integrals. Therefore, from Eq. (4.2),

$$R_q^2 = \frac{1}{l}\int_0^l y^2 \, dx = \frac{1}{l}\int_0^l a^2 \sin^2 \frac{2\pi x}{l} \, dx$$

Evaluating the integral,

$$\begin{aligned} R_q^2 &= \frac{a^2}{l}\frac{l}{2\pi}\left[\frac{2\pi x}{2l} - \frac{1}{4}\sin\frac{4\pi x}{l}\right]_0^l \\ &= \frac{a^2}{2\pi}\left[(\pi - 0) - (0 - 0)\right] = \frac{a^2}{2} \end{aligned}$$

So that $R_q = \frac{a}{\sqrt{2}}$, and

$$\frac{R_a}{R_q} = \frac{2a/\pi}{a/\sqrt{2}} = \frac{2\sqrt{2}}{\pi} \approx 0.90$$

(b) For a saw-tooth profile, we can use symmetry to evaluate R_a and R_q over one-fourth of

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the saw tooth. The equation for the curve over this range is:

$$y = \frac{4a}{l}x$$

so that, from Eq. (4.1),

$$R_a = \frac{4}{l}\int_0^{l/4} \frac{4ax}{l}dx$$

Evaluating the integral,

$$R_a = \frac{16a}{l^2}\left(\frac{1}{2}x^2\right)_0^{l/4} = \frac{16a}{l^2}\frac{1}{2}\left(\frac{l^2}{16} - 0\right) = \frac{a}{2}$$

From Eq. (4.2),

$$R_q^2 = \frac{4}{l}\int_0^{l/4} y^2\,dx = \frac{4}{l}\int_0^{l/4} \frac{16a^2}{l^2}x^2\,dx$$

Evaluating the integral,

$$R_q^2 = \frac{64a^2}{l^3}\left(\frac{1}{3}x^3\right)_0^{l/4} = \frac{64a^2}{l^3}\frac{1}{3}\frac{l^3}{64} = \frac{a^2}{3}$$

Therefore, $R_q = \frac{a}{\sqrt{3}}$ and

$$\frac{R_a}{R_q} = \frac{a/2}{a/\sqrt{3}} = \frac{\sqrt{3}}{2} \approx 0.866$$

(c) For a square wave with amplitude a,

$$R_a = \frac{1}{l}\int_0^l a\,dx = \frac{a}{l}(x)_0^l = a$$

and

$$R_q^2 = \frac{1}{l}\int_0^l a^2\,dx = \frac{a^2}{l}(x)_0^l = a^2$$

so that $R_q = a$. Therefore,

$$\frac{R_a}{R_q} = \frac{a}{a} = 1.0$$

4.58 Refer to Fig. 4.7b and make measurements of the external and internal diameters(in the horizontal direction in the photograph) of the four specimens shown. Remembering that in plastic deformation the volume of the rings remains constant, calculate (a) the reduction in height and (b) the coefficient of friction for each of the three compressed specimens.

The volume of the original specimen is (see Fig. 4.8 on p. 142):

$$V = \frac{\pi h}{4}\left(d_o^2 - d_i^2\right) = \frac{\pi(0.25)}{4}\left(0.75^2 - 0.375^2\right)$$

or $V = 0.0828$ in^3. Note that the volume must remain constant, so that

$$\frac{h\pi}{4}\left(d_o^2 - d_i^2\right) = 0.0828 \text{ in}^3$$

or

$$h = \frac{0.105}{d_o^2 - d_i^2}$$

Specimen 1 has not been deformed, so its dimensions are taken from Fig. 4.8. The remaining dimensions are scaled to be consistent with these values. The height value cannot be directly measured because of the angle of view in the figure; so these are calculated from volume constancy. Sample measurements are as follows:

ID	d_i d_i (in.)	d_o (in.)	h (in.)
1	0.375	0.75	0.25
2	0.477	0.97	0.147
3	0.282	1.04	0.104
4	0.1757	1.04	0.100

The reduction in height is calculated from

$$\%\text{ Reduction in height} = \frac{h_o - h_f}{h_o} \times 100$$

and the values of the coefficient of friction are then obtained from Fig. 4.8a on p. 142 to obtain the following:

ID	% Reduction in height	% Reduction in d_i	μ
1	0	0	—
2	41.2	-27.2	0.01
3	58.4	24.8	0.10
4	60	53.1	0.20

Note that the fricton coefficient increases as the test progresses. This is commonly observed in lubricated specimens, where the lubricant film is initially thick, but breaks down as the contact area between the ring and die increases.

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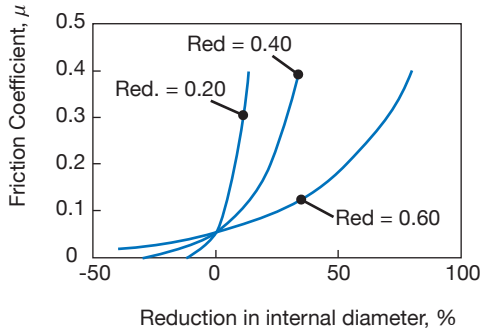
4.59 Using Fig. 4.8a, make a plot of the coefficient of friction versus the change in internal diameter for a reduction in height of (1) 25%, (2) 50%, and (3) 60%.

Typical data obtained from Fig. 4.8a on p. 142 are summarized in the table below. Note that particular results may vary.

	% Change in Internal Diameter		
μ	20% Red. in height	40% Red. in height	60% Red. in height
0	-12	-30	—
0.02	-7	-16	-40
0.03	-4	-10	-24
0.04	-3	-5	-12
0.055	0	0	0
0.1	4	10	25
0.2	8	22	53
0.3	11	28	70
0.4	13	34	80
0.577	15	38	—

The plot follows:



4.60 In Example 4.1, assume that the coefficient of friction is 0.20. If all other initial parameters remain the same, what is the new internal diameter of the ring specimen?

If μ=0.20, Fig. 4.8a on p. 142 shows that the reduction in inner diameter is about 34% for a reduction in height of 50%. Since the original ID is 15 mm, we therefore have

$$\frac{15 \text{ mm} - \text{ID}_{\text{final}}}{15 \text{ mm}} = 0.34$$

or $\text{ID}_{\text{final}} = 9.9$ mm.

4.61 How would you go about estimating forces required for roller burnishing? (*Hint:* Consider hardness testing.)

The procedure would consist of first determining the contact area between the roller and the surface being burnished. The force is then the product of this area and the compressive stress on the workpiece material. Because of the constrained volume of material subjected to plastic deformation, the level of this stress is on the order of the hardness of the material, as described in Section 2.6.8 on p. 54, or about three times the yield stress for cold-worked metals; see also Fig. 2.24 on p. 55.

4.62 Estimate the plating thickness in electroplating a 50-mm solid metal ball using a current of 1 A and a plating time of 2 hours. Assume that $c = 0.08$.

Note that the surface area of a sphere is $A = 4\pi r^2$, so that the volume of the plating is $V = 4\pi r^2 h$, where h is the plating thickness. From Eq. (4.7) on p. 159,

$$V = cIt = 4\pi r^2 h$$

Solving for the plating thickness, and using proper units, we find

$$h = \frac{cIt}{4\pi r^2} = \frac{(0.08)(1)(7200)}{4\pi(25)^2} = 0.073 \text{ mm}$$

4.63 Assume that a steel rule expands by 1% because of an increase in environmental temperature. What will be the indicated diameter of a shaft whose actual diameter is 50.00 mm?

The indicated diameter will be 50.00 - 0.01(50.00) = 49.50 mm.

4.64 Examine Eqs. (4.2) and (4.10). What is the relationship between R_q and σ? What would be the equation for the standard deviation of a continuous curve?

The two equations are very similar. Note that if the mean is zero, then Eq. (4.10) on p. 178 is almost exactly the same as Eq. (4.2) on p. 134. When a large number of data points are considered, the equations are the same. R_q roughness can actually be thought of as the standard deviation of a curve about its mean line. The standard deviation of a continuous curve can

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simply be expressed by the analog portion of Eq. (4.2):

$$\sigma = \sqrt{\frac{1}{l}\int_0^l y^2\,dx}$$

or, if the mean is μ,

$$\sigma = \sqrt{\frac{1}{l}\int_0^l (y-\mu)^2\,dx}$$

4.65 Calculate the control limits for averages and ranges for the following: number of samples = 7; $\bar{\bar{x}} = 50$; $\bar{R} = 7$.

From Table 4.3, we find that for a sample size of 7, we have $A_2 = 0.419$, $D_4 = 1.924$ and $D_3 = 0.078$. Equations (4.11) and (4.12) give the upper and lower control limits for the averages as

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = 50 + (0.419)(7) = 52.933$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = 50 - (0.419)(7) = 47.067$$

For the ranges, Eqs. (4.13) and (4.14) yield

$$\text{UCL}_R = D_4\bar{R} = (1.924)(7) = 13.468$$

$$\text{LCR}_R = D_3\bar{R} = (0.078)(7) = 0.546$$

4.66 Calculate the control limits for the following: number of samples = 7; $\bar{\bar{x}} = 40.5$; $\text{UCL}_R = 4.85$.

From Table 4.3, we find that for a sample size of 7, we have $A_2 = 0.419$, $D_4 = 1.924$ and $D_3 = 0.078$. If the UCL_R is 4.85, then from Eq. (4.14),

$$\text{UCL}_R = D_4\bar{R}$$

solving for $\bar{R}$,

$$\bar{R} = \frac{\text{UCL}_R}{D_4} = \frac{4.85}{1.924} = 2.521$$

Therefore, Eqs. (4.11) and (4.12) give the upper and lower control limits for the averages as

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = (40.5) + (0.419)(2.521) = 41.556$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = (40.5) - (0.419)(2.521) = 39.444$$

Equation (4.14) gives:

$$\text{LCL}_R = D_3\bar{R} = (0.078)(2.521) = 0.197$$

4.67 In an inspection with a sample size of 10 and a sample number of 40, it was found that the average range was 10 and the average of averages was 75. Calculate the control limits for averages and ranges.

From Table 4.3, we find that for a sample size of 10, we have $A_2 = 0.308$, $D_4 = 1.777$ and $D_3 = 0.223$. Equations (4.11) and (4.12) on p. 180 give the upper and lower control limits for the averages as

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = (75) + (0.308)(10) = 78.080$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = (75) - (0.308)(10) = 71.920$$

For the ranges, Eqs. (4.13) and (4.14) yield

$$\text{UCL}_R = D_4\bar{R} = (1.777)(10) = 17.77$$

$$\text{LCR}_R = D_3\bar{R} = (0.223)(10) = 2.23$$

4.68 Determine the control limits for the data shown in the following table:

x_1	x_2	x_3	x_4
0.65	0.75	0.67	0.65
0.69	0.73	0.70	0.68
0.65	0.68	0.65	0.61
0.64	0.65	0.60	0.60
0.68	0.72	0.70	0.66
0.70	0.74	0.65	0.71

Since the number of samples is 4, from Table 4.3 on p. 180 we find that $A_2 = 0.729$, $D_4 = 2.282$, and $D_3 = 0$. We calculate averages and ranges and fill in the chart as follows:

x_1	x_2	x_3	x_4	$\bar{x}$	R
0.65	0.75	0.67	0.65	0.6800	0.10
0.69	0.73	0.70	0.68	0.7000	0.05
0.65	0.68	0.65	0.61	0.6475	0.07
0.64	0.65	0.60	0.60	0.6225	0.05
0.68	0.72	0.70	0.66	0.6900	0.06
0.70	0.74	0.65	0.71	0.7000	0.09

Therefore, the average of averages is $\bar{\bar{x}} = 0.6733$, and the average range is $\bar{R} = 0.07$. Eqs. (4.11) and (4.12) give the upper and lower control limits for the averages as

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = (0.6733) + (0.729)(0.07)$$

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or $\text{UCL}_{\bar{x}}$=0.7243.

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = (0.6733) - (0.729)(0.07)$$

or $\text{LCL}_{\bar{x}}$=0.6223. For the ranges, Eqs. (4.13) and (4.14) yield

$$\text{UCL}_R = D_4\bar{R} = (2.282)(0.07) = 0.1600$$

$$\text{LCR}_R = D_3\bar{R} = (0)(0.07) = 0$$

4.69 Calculate the mean, median and standard deviation for all of the data in Problem 4.68.

The mean is given by Eq. (4.8) on p. 178 as

$$\bar{x} = \frac{0.65 + 0.75 + 0.67 + \ldots + 0.71}{24} = 0.6733$$

The median is obtained by arranging the data and finding the value that defines where 50% of the data is above that value. For the data in Problem 4.68, the median is between 0.67 and 0.68, so it is reported as 0.675. The standard deviation is given by Eq. (4.10) on p. 178 as

$$\sigma = \sqrt{\frac{(0.65 - 0.6733)^2 + \ldots + (0.71 - 0.6733)^2}{23}}$$

which in this case is determined as $\sigma = 0.0411$.

4.70 The average of averages of a number of samples of size 7 was determined to be 125. The average range was 17.82, and the standard deviation was 5.85. The following measurements were taken in a sample: 120, 132, 124, 130, 118, 132, 121, and 127. Is the process in control?

For a sample size of 7, we note from Table 4.3 on p. 180 that $A_2 = 0.419$, $D_4 = 1.924$, and $D_3 = 0.078$. Equations (4.11) and (4.12) give the upper and lower control limits for the averages as

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = (125) + (0.419)(17.82) = 132.46$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = (125) - (0.419)(17.82) = 117.53$$

For the ranges, Eqs. (4.13) and (4.14) yield

$$\text{UCL}_R = D_4\bar{R} = (1.924)(17.82) = 34.28$$

$$\text{LCR}_R = D_3\bar{R} = (0.078)(17.82) = 1.390$$

For the sample shown, the average is $\bar{x} = 125.3$ and the range is $R = 132 - 118 = 14$. These are both within their respective control limits, therefore the process is in control. Note that the standard deviation is 5.85, and Eq. (4.14) on p. 180 allows an alternative method of calculation of the average range.

4.71 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

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Chapter 5

Metal-Casting Processes and Equipment; Heat Treatment

Questions

5.1 Describe the characteristics of (1) an alloy, (2) pearlite, (3) austenite, (4) martensite, and (5) cementite.

(a) Alloy: composed of two or more elements, at least one element is a metal. The alloy may be a solid solution or it may form intermetallic compounds.

(b) Pearlite: a two-phase aggregate consisting of alternating lamellae of ferrite and cementite; the closer the pearlite spacing of lamellae, the harder the steel.

(c) Austenite: also called gamma iron, it has a fcc crystal structure which allows for a greater solubility of carbon in the crystal lattice. This structure also possesses a high ductility, which increases the steel's formability.

(d) Martensite: forms by quenching austenite. It has a bct (body-centered tetragonal) structure, and the carbon atoms in interstitial positions impart high strength. It is hard and very brittle.

(e) Cementite: also known as iron-carbide (Fe_3C), it is a hard and brittle intermetallic phase.

5.2 What are the effects of mold materials on fluid flow and heat transfer?

The most important factor is the thermal conductivity of the mold material; the higher the conductivity, the higher the heat transfer and the greater the tendency for the fluid to solidify, hence possibly impeding the free flow of the molten metal. Also, the higher the cooling rate of the surfaces of the casting in contact with the mold, the smaller the grain size and hence the higher the strength. The type of surfaces developed in the preparation of mold materials may also be different. For example, sand-mold surfaces are likely be rougher than those of metal molds whose surfaces can be prepared to varying degrees of roughness, including the directions of roughness (lay).

5.3 How does the shape of graphite in cast iron affect its properties?

The shape of graphite in cast irons has the following basic forms:

(a) Flakes. Graphite flakes have sharp edges which act as stress raisers in tension. This shape makes cast iron low in tensile strength and ductility, but it still has high compressive strength. On the other hand, the flakes also act as vibration dampers, a characteristic important in damping of machine-tool bases and other structures.

(b) Nodules. Graphite can form nodules or spheroids when magnesium or cerium is

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added to the melt. This form has increased ductility, strength, and shock resistance compared to flakes, but the damping ability is reduced.

(c) Clusters. Graphite clusters are much like nodules, except that they form from the breakdown of white cast iron upon annealing. Clusters have properties that are basically similar to flakes.

(d) Compacted flakes. These are short and thick flakes with rounded edges. This form has properties that are between nodular and flake graphite.

5.4 Explain the difference between short and long freezing ranges. How are they determined? Why are they important?

Freezing range is defined by Eq. (5.3) on p. 196 in terms of temperature difference. Referring to Fig. 5.6 on p. 197, note that once the phase diagram and the composition is known, we can determine the freezing range, $T_L - T_S$. As described in Section 5.3.2 on p. 196, the freezing range has an important influence on the formation and size of the mushy zone, and, consequently, affects structure-property relationships of the casting.

5.5 We know that pouring molten metal at a high rate into a mold has certain disadvantages. Are there any disadvantages to pouring it very slowly? Explain.

There are disadvantages to pouring metal slowly. Besides the additional time needed for mold filling, the liquid metal may solidify or partially solidify while still in the gating system or before completely filling the mold, resulting in an incomplete or partial casting. This can have extremely detrimental effects in a tree of parts, as in investment casting.

5.6 Why does porosity have detrimental effects on the mechanical properties of castings? Which physical properties are also affected adversely by porosity?

Pores are, in effect, internal discontinuities that are prone to cracking and crack propagation. Thus, the toughness of a material will decrease as a result of porosity. Furthermore, the presence of pores in a piece of metal under tension indicates that the material around the pores has to support a greater load than if no pores were present; thus, the strength is also lowered. Considering thermal and electrical conductivity, an internal defect such as a pore decreases both the thermal and electrical conductivity, nting that air is a very poor conductor.

5.7 A spoked hand wheel is to be cast in gray iron. In order to prevent hot tearing of the spokes, would you insulate the spokes or chill them? Explain.

Referring to Table 5.1 on p. 206, we note that, during solidification, gray iron undergoes an expansion of 2.5%. Although this fact may suggest that hot tearing cannot occur, consideration must also be given to significant contraction of the spokes during cooling. Since the hot-tearing tendency will be reduced as the strength increases, it would thus be advisable to chill the spokes to develop this strength.

5.8 Which of the following considerations are important for a riser to function properly? (1) Have a surface area larger than that of the part being cast. (2) Be kept open to atmospheric pressure. (3) Solidify first. Explain.

Both (1) and (3) would result in a situation contrary to a riser's purpose. That is, if a riser solidifies first, it cannot feed the mold cavity. However, concerning (2), an open riser has some advantages over closed risers. Recognizing that open risers have the danger of solidifying first, they must be sized properly for proper function. But if the riser is correctly sized so that it remains a reservoir of molten metal to accommodate part shrinkage during solidification, an open riser helps exhaust gases from the mold during pouring, and can thereby eliminate some associated defects. A so-called blind riser that is not open to the atmosphere may cause pockets of air to be trapped, or increased dissolution of air into the metal, leading to defects in the cast part. For these reasons, the size and placement of risers is one of the most difficult challenges in designing molds.

5.9 Explain why the constant C in Eq. (5.9) depends on mold material, metal properties, and temperature.

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The constant C takes into account various factors such as the thermal conductivity of the mold material and external temperature. For example, Zircon sand has a higher thermal conductivity than basic silica sand, and as a result, a casting in Zircon (of equal volume and surface area) will require less time to solidify than that cast in silica.

5.10 Explain why gray iron undergoes expansion, rather than contraction, during solidification.

As gray cast iron solidifies, a period of graphitization occurs during the final stages, which causes an expansion that counteracts the shrinkage of the metal. This results in an overall expansion.

5.11 How can you tell whether a cavity in a casting are due to porosity or to shrinkage?

Evidence of which type of porosity is present, i.e., gas or shrinkage, can be gained by studying the location and shape of the cavity. If the porosity is near the mold surface, core surface, or chaplet surface, it is most likely to be gas porosity. However, if the porosity occurs in an area considered to be a hot spot in the casting (see Fig. 5.37 on p. 249), it is most likely to be shrinkage porosity. Furthermore, gas porosity has smooth surfaces (much like the holes in Swiss cheese) and is often, though not always, generally spherical in shape. Shrinkage porosity has a more textured and jagged surface, and is generally irregular in shape.

5.12 Explain the reasons for hot tearing in castings.

Hot tearing is a result of tensile stresses that develop upon contraction during solidification in molds and cores if they are not sufficiently collapsible and/or do not allow movement under the resulting pressure during shrinkage.

5.13 Would you be concerned about the fact that a portion of an internal chill is left within the casting? What materials do you think chills should be made of, and why?

The fact that a part of the chill remains within the casting should be a consideration in the design of parts to be cast. The following factors are important:

(a) The material from which the chill is made should be compatible with the metal being cast (it should have approximately the same composition of the metal being poured).

(b) The chill must be clean, that is, without any lubricant or coating on the surface, because any gas evolved when the molten metal contacts the chill may not readily escape.

(c) The chill may not fuse with the casting, developing regions of weakness or stress concentration. If these factors are understood and provided for, the fact that a piece of the chill remains within the casting is generally of no significant concern.

5.14 Are external chills as effective as internal chills? Explain.

The effectiveness will depend on the location of the region to be chilled in the mold. If a region needs to be chilled (say, for example, to directionally solidify a casting), an external chill can be as effective as an internal chill. Often, however, chilling is required at some depth beneath the surface of a casting to be effective. For this condition an internal chill would be more effective.

5.15 Do you think early formation of dendrites in a mold can impede the free flow of molten metal into the mold? Explain.

Consider the solidification of an alloy with a very long freezing range. The mushy zone for this alloy will also be quite large (see Fig. 5.6). Since the mushy condition consists of interlacing dendrites surrounded by liquid, it is apparent that this condition will restrict fluid flow, as also confirmed in practice.

5.16 Is there any difference in the tendency for shrinkage void formation for metals with short freezing and long freezing ranges, respectively? Explain.

In an alloy with a long freezing range, the presence of a large mushy zone is more likely to occur, and thus the formation of miocroporosity. However, in an alloy with a short freezing range, the formation of gross shrinkage voids is more likely to occur.

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5.17 It has long been observed by foundrymen that low pouring temperatures (that is, low superheat) promote equiaxed grains over columnar grains. Also, equiaxed grains become finer as the pouring temperature decreases. Explain the reasons for these phenomena.

Equiaxed grains are present in castings near the mold wall where rapid cooling and solidification take place by heat transfer through the relatively cool mold. With low pouring temperature, cooling to the solidification temperature is faster because there is less heat stored in the molten metal. With a high pouring temperature, cooling to the solidification temperature is slower, especially away from the mold wall. The mold still dissipates heat, but the metal remains molten for a longer period of time, thus producing columnar grains in the direction of heat conduction. As the pouring temperature is decreased, equiaxed grains should become finer because the cooling is more rapid and large grains do not have time to form from the molten metal.

5.18 What are the reasons for the large variety of casting processes that have been developed over the years?

By the student. There are several acceptable answers depending on the interpretation of the problem by the student. Students may approach this as processes that are application driven, material driven, or economics driven. For example, while investment casting is more expensive than sand casting, closer dimensional tolerances and better surface finish are possible. Thus, for certain parts such as barrels for handguns, investment casting is preferable. Consider also the differences between the hot- and cold-chamber permanent-mold casting operations.

5.19 Why can blind risers be smaller than open-top risers?

Risers are used as reservoirs for a casting in regions where shrinkage is expected to occur, i.e, areas which are the last to solidify. Thus, risers must be made large enough to ensure that they are the last to solidify. If a riser solidifies before the cavity it is to feed, it is useless. As a result, an open riser in contact with air must be larger to ensure that it will not solidify first. A blind riser is less prone to this phenomenon, as it is in contact with the mold on all surfaces; thus a blind riser may be made smaller.

5.20 Would you recommend preheating the molds in permanent-mold casting? Also, would you remove the casting soon after it has solidified? Explain.

Preheating the mold in permanent-mold casting is advisable in order to reduce the chilling effect of the metal mold which could lead to low metal fluidity and the problems that accompany this condition. Also, the molds are heated to reduce thermal damage which may result from repeated contact with the molten metal. Considering casting removal, the casting should be allowed to cool in the mold until there is no danger of distortion or developing defects during shakeout. While this may be a very short period of time for small castings, large castings may require an hour or more.

5.21 In a sand-casting operation, what factors determine the time at which you would remove the casting from the mold?

This question is an important one for any casting operation, not just sand casting, because a decrease in production time will result in a decrease in product cost. Therefore, a casting ideally should be removed at the earliest possible time. Factors which affect time are the thermal conductivity of the mold-material and of the cast metal, the thickness and the overall size of the casting, and the temperature at which the metal is being poured.

5.22 Explain why the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness.

Because the metal die acts as a heat sink for the molten metal, the metal chills rapidly, developing a fine-grain hard skin with higher strength. As a result, the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness.

5.23 We note that the ductility of some cast alloys is very low (see Fig. 5.13). Do you think this should be a significant concern in engineering applications of castings? Explain.

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The low ductility of some cast alloys should certainly be taken into consideration in the engineering application of the casting. The low ductility will:

(a) affect properties, such as toughness and fatigue,

(b) have a significant influence on further processing and finishing of the casting, i.e., machining processes, such as milling, drilling, and tapping, and

(c) possibly affect tribological behavior.

It should be noted that many engineering applications do not require high ductility; for example, when stresses are sufficiently small to ensure the material remains elastic and where impact loads do not occur.

5.24 The modulus of elasticity of gray iron varies significantly with its type, such as the ASTM class. Explain why.

Because the shape, size, and distribution of the second-phase (i.e., the graphite flakes) vary greatly for gray cast irons, there is a large corresponding variation of properties attainable. The elastic modulus, for example, is one property which is affected by this factor.

5.25 List and explain the considerations involved in selecting pattern materials.

Pattern materials have a number of important material requirements. Often, they are machined, thus good machinability is a requirement. The material should be sufficiently stiff to allow good shape development. The material must have sufficient wear and corrosion resistance so that the pattern has a reasonable life. The economics of the operation is affected also by material cost.

5.26 Why is the investment-casting process capable of producing fine surface detail on castings?

The surface detail of the casting depends on the quality of the pattern surface. In investment casting, for example, the pattern is made of wax or a thermoplastic poured or injected into a metal die with good surface finish. Consequently, surface detail of the casting is very good and can be controlled. Furthermore, the coating on the pattern (which then becomes the mold) consists of very fine silica, thus contributing to the fine surface detail of the cast product.

5.27 Explain why a casting may have a slightly different shape than the pattern used to make the mold.

After solidification, shrinkage continues until the casting cools to room temperature. Also, due to surface tension, the solidifying metal will, when surface tension is high enough, not fully conform to sharp corners and other intricate surface features. Thus, the cast shape will generally be slightly different from that of the pattern used.

5.28 Explain why squeeze casting produces parts with better mechanical properties, dimensional accuracy, and surface finish than expendable-mold processes.

The squeeze-casting process consists of a combination of casting and forging. The pressure applied to the molten metal by the punch, or upper die, keeps the entrapped gases in solution, and thus porosity is generally not found in these products. Also, the rapid heat transfer results in a fine microstructure with good mechanical properties. Due to the applied pressure and the type of die used, i.e., metal, good dimensional accuracy and surface finish are typically found in squeeze-cast parts.

5.29 Why are steels more difficult to cast than cast irons?

The primary reason steels are more difficult to cast than cast irons is that they melt at a higher temperature. The high temperatures complicate mold material selection, preparation, and techniques involved for heating and pouring of the metal.

5.30 What would you recommend to improve the surface finish in expendable-mold casting processes?

One method of improving the surface finish of castings is to use what is known as a facing sand, such as Zircon. This is a sand having better properties (such as permeability and surface finish) than bulk sand, but is generally more expensive. Thus, facing sand is used as a first

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layer against the pattern, with the rest of the mold being made of less expensive (silica) sand.

5.31 You have seen that even though die casting produces thin parts, there is a limit to the minimum thickness. Why can't even thinner parts be made by this process?

Because of the high thermal conductivity that metal dies exhibit, there is a limiting thickness below which the molten metal will solidify prematurely before filling the mold cavity. Also, the finite viscosities of the molten metal (which increases as it begins to cool) will require higher pressures to force the metal into the narrow passages of the die cavities.

5.32 What differences, if any, would you expect in the properties of castings made by permanent-mold vs. sand-casting methods?

As described in the text, permanent-mold castings generally possess better surface finish, closer tolerances, more uniform mechanical properties, and more sound thin-walled sections than sand castings. However, sand castings generally can have more intricate shapes, larger overall size, and lower in cost (depending upon the alloy) than permanent-mold castings.

5.33 Which of the casting processes would be suitable for making small toys in large numbers? Explain.

This is an open-ended problem, and the students should give a rationale for their choice. Refer also to Table 5.2 and note that die casting is one of the best processes for this application. The student should refer to the application requiring large production runs, so that tooling cost per casting can be low, the sizes possible in die casting are suitable for such toys, and the dimensional tolerances and surface finish are acceptable.

5.34 Why are allowances provided for in making patterns? What do they depend on?

Shrinkage allowances on patterns are corrections for the shrinkage that occurs upon solidification of the casting and its subsequent contraction while cooling to room temperature. The allowance will therefore depend on the amount of contraction an alloy undergoes.

5.35 Explain the difference in the importance of drafts in green-sand casting vs. permanent-mold casting.

Draft is provided to allow the removal of the pattern without damaging the mold. If the mold material is sand and has no draft, the mold cavity is likely to be damaged upon pattern removal, due to the low strength of the sand mold. However, a die made of high-strength steel, which is typical for permanent-mold castings, is not at all likely to be damaged during the removal of the part; thus smaller draft angles can be employed.

5.36 Make a list of the mold and die materials used in the casting processes described in this chapter. Under each type of material, list the casting processes that are used, and explain why these processes are suitable for that particular mold or die material.

This is an open-ended problem, and students should be encouraged to develop an answer based on the contents of this chapter. An example of an acceptable answer would, in a brief form, be:

- Sand: Used because of its ability to resist very high temperatures, availability, and low cost. Used for sand, shell, expanded-pattern, investment, and ceramic-mold casting processes.
- Metal: Such as steel or iron. Results in excellent surface finish and good dimensional accuracy. Used for die, slush, pressure, centrifugal, and squeeze-casting processes.
- Graphite: Used for conditions similar to those for metal molds; however, lower pressures should be employed for this material. Used mainly in pressure- and centrifugal-casting.
- Plaster of paris: Used in plaster-mold casting for the production of relatively small components, such as fittings and valves.

5.37 Explain why carbon is so effective in imparting strength to iron in the form of steel.

Carbon has an atomic radius that is about 57% of the iron atom, thus it occupies an interstitial position in the iron unit cell (see Figs. 3.2 on

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p. 84 and 3.9 on p. 90). However, because its radius is greater than that of the largest hole between the Fe atoms, it strains the lattice, thus interfering with dislocation movement and leading to strain hardening. Also, the size of the carbon atom allows it to have a high solubility in the fcc high-temperature phase of iron (austenite). At low temperatures, the structure is bcc and has a very low solubility of carbon atoms. On quenching, the austenitic structure transforms to body-centered tetragonal (bct) martensite, which produces high distortion in the crystal lattice. Because it is higher, the strength increase is more than by other element additions.

5.38 Describe the engineering significance of the existence of a eutectic point in phase diagrams.

The eutectic point corresponds to a composition of an alloy that has a lowest melting temperature for that alloy system. The low melting temperature associated with a eutectic point can, for example, help in controlling thermal damage to parts during joining, as is done in soldering. (See Section 12.13.3 starting on p. 776).

5.39 Explain the difference between hardness and hardenability.

Hardness represents the material's resistance to plastic deformation when indented (see Section 2.6 starting on p. 51), while hardenability is the material's capability to be hardened by heat treatment. (See also Section 5.11.1 starting on p. 236).

5.40 Explain why it may be desirable or necessary for castings to be subjected to various heat treatments.

The morphology of grains in an as-cast structure may not be desirable for commercial applications. Thus, heat treatments, such as quenching and tempering (among others), are carried out to optimize the grain structure of castings. In this manner, the mechanical properties can be controlled and enhanced.

5.41 Describe the differences between case hardening and through hardening insofar as engineering applications are concerned.

Case hardening is a treatment that hardens only the surface layer of the part (see Table 5.7 on p. 242). The bulk retains its toughness, which allows for blunting of surface cracks as they propagate inward. Case hardening generally induces compressive residual stresses on the surface, thus retarding fatigue failure. Through hardened parts have a high hardness across the whole part; consequently, a crack could propagate easily through the cross section of the part, causing major failure.

5.42 *Type metal* is a bismuth alloy used to cast type for printing. Explain why bismuth is ideal for this process.

When one considers the use of type or for precision castings such as mechanical typewriter impressions, one realizes that the type tool must have extremely high precision and smooth surfaces. A die casting using most metals would have shrinkage that would result in the distortion of the type, or even the metal shrinking away from the mold wall. Since bismuth expands during solidification, the molten metal can actually expand to fill molds fully, thereby ensuring accurate casting and repeatable typefaces.

5.43 Do you expect to see larger solidification shrinkage for a material with a bcc crystal structure or fcc? Explain.

The greater shrinkage would be expected from the material with the greater packing efficiency or atomic packing factor (APF) in a solid state. Since the APF for fcc is 0.74 and for bcc it is 0.68, one would expect a larger shrinkage for a material with a fcc structure. This can also been seen from Fig. 3.2 on p. 84. Note, however, that for an alloy, the answer is not as simple, since it must be determined if the alloying element can fit into interstitial positions or serves as a substitutional element.

5.44 Describe the drawbacks to having a riser that is (a) too large, or (b) too small.

The main drawbacks to having a riser too large are: the material in the riser is eventually scrapped and has to be recycled; the riser hass to be cut off, and a larger riser will cost more

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to machine; an excessively large riser slows solidification; the riser may interfere with solidification elsewhere in the casting; the extra metal may cause buoyancy forces sufficient to separate the mold halves, unless they are properly weighted or clamped. The drawbacks to having too small a riser are mainly associated with defects in the casting, either due to insufficient feeding of liquid to compensate for solidification shrinkage, or shrinkage pores because the solidification front is not uniform.

5.45 If you were to incorporate lettering on a sand casting, would you make the letters protrude from the surface or recess into the surface? What if the part were to be made by investment casting?

In sand casting, where a pattern must be prepared and used, it is easier to produce letters and numbers by machining them into the surface of a pattern; thus the pattern will have recessed letters. The sand mold will then have protruding letters, as long as the pattern is faithfully reproduced. The final part will then have recessed letters.

In investment casting, the patterns are produced through injection molding. It is easier to include recessed lettering in the injection molding die (instead of machining protruding letters). Thus, the mold will have recessed letters and the pattern will have protruding letters. Since the pattern is a replica of the final part, the part will also have protruding letters.

In summary, it is generally easier to produce recessed letters in sand castings and protruding letters in investment casting.

5.46 List and briefly explain the three mechanisms by which metals shrink during casting.

Metals shrink by:

(a) Thermal contraction in the liquid phase from superheat temperature to solidification temperature,

(b) Solidification shrinkage, and

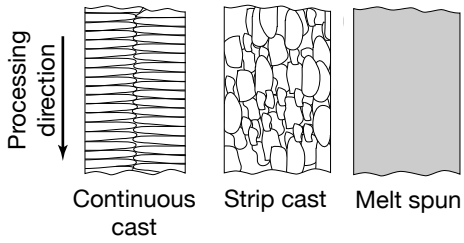
(c) Thermal contraction in the solid phase from the solidification temperature to room temperature.

5.47 Explain the significance of the "tree" in investment casting.

The tree is important because it allows simultaneous casting of several parts. Since significant labor is involved in the production of each mold, this strategy of increasing the number of parts that are poured per mold is critical to the economics of investment casting.

5.48 Sketch the microstructure you would expect for a slab cast through (a) continuous casting, (b) strip casting, and (c) melt spinning.

The microstructures are as follows:



Note that the continuous cast structure shows the columnar grains growing away from the mold wall. The strip-cast metal has been hot rolled immediately after solidification, and is shown as quenched, prior it is annealed to obtain an equiaxed structure. The melt-spun structure solidifies so rapidly that there are no clear grains (an amorphous metal).

5.49 The general design recommendations for a well in sand casting are that (a) its diameter should be twice the sprue exit diameter, and (b) the depth should be approximately twice the depth of the runner. Explain the consequences of deviating from these rules.

Refer to Figure 5.10 for terminology used in this problem.

(a) Regarding this rule, if the well diameter is much larger than twice the exit diameter, liquid will not fill the well and aspiration of the molten metal may result. On the other hand, if the diameter is small compared to the sprue exit diameter, and recognizing that wells are generally not tapered, then there is a fear of aspiration within the well (see the discussion of sprue profile in Section 5.4 starting on p. 199.

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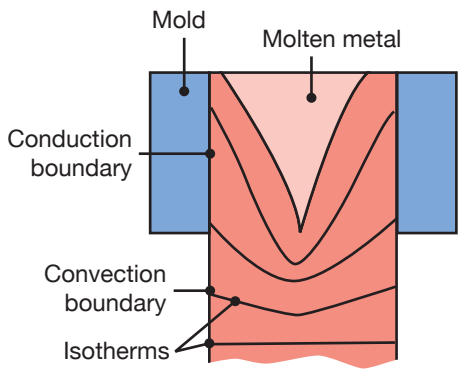
(b) If the well is not deeper than the runner, then turbulent metal first splashed into the well is immediately fed into the casting, leading to aspiration and associated defects. If the well is much deeper, then the metal remains in the well and can solidify prematurely.

5.50 Describe the characteristics of thixocasting and rheocasting.

Thixocasting and rheocasting involve casting operations where the alloy is in the slushy stage. Often, ultrasonic vibrations will be used to ensure that dendrites remain in solution, so that the metal is a slurry of molten continuous phase and suspended particles. In such casting operations, the molten metal has a lower superheat and, therefore, requires less cycle time, and shrinkage defects and porosity can be decreased. This is further described in Section 5.10.6 starting on p. 233.

5.51 Sketch the temperature profile you would expect for (a) continuous casting of a billet, (b) sand casting of a cube, (c) centrifugal casting of a pipe.

This would be an interesting finite-element assignment if such software is made available to the students. Consider continuous casting. The liquid portion has essentially a constant temperature, as there is significant stirring of the liquid through the continuous addition of molten metal. The die walls extract heat, and the coolant spray at the die exterior removes heat even more aggressively. Thus, a sketch of the isotherms in continuous casting would be as follows:



The cube and the pipe are left to be completed by the student.

5.52 What are the benefits and drawbacks to having a pouring temperature that is much higher than the metal's melting temperature? What are the advantages and disadvantages in having the pouring temperature remain close to the melting temperature?

If the pouring temperature is much higher than that of the mold temperature, there is less danger that the metal will solidify in the mold, and it is likely that even intricate molds can be fully filled. This situation makes runners, gates, wells, etc., easier to design because their cross sections are less critical for complete mold filling. The main drawback is that there is an increased likelihood of shrinkage pores, cold shuts, and other defects associated with shrinkage. Also there is an increased likelihood of entrained air since the viscosity of the metal will be lower at the higher pouring temperature. If the pouring temperature is close to the melting temperature, there will be less likelihood of shrinkage porosity and entrained air. However, there is the danger of the molten metal solidifying in a runner before the mold cavity is completely filled; this may be overcome with higher injection pressures, but clearly has a cost implication.

5.53 What are the benefits and drawbacks to heating the mold in investment casting before pouring in the molten metal?

Heating the mold in investment casting is advisable in order to reduce the chilling effect of the mold, which otherwise could lead to low metal fluidity and the problems that accompany this condition. Molds are usually preheated to some extent. However, excessive heating will compromise the strength of the mold, resulting in erosion and associated defects.

5.54 Can a chaplet also act as a chill? Explain.

A chaplet is used to position a core. It has a geometry that can either rest against a mold face or it can be inserted into a mold face. If the chaplet is a thermally conductive material, it can also serve as a chill.

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5.55 Rank the casting processes described in this chapter in terms of their solidification rate. For example, which processes extract heat the fastest from a given volume of metal and which is the slowest?

There is, as expected, some overlap between the various processes, and the rate of heat transfer can be modified whenever desired. However, a general ranking in terms of rate of heat extraction is as follows: Die casting (cold chamber), squeeze casting, centrifugal casting, slush casting, die casting (hot chamber), permanent mold casting, shell mold casting, investment casting, sand casting, lost foam, ceramic-mold casting, and plaster-mold casting.

5.56 The heavy regions of parts typically are placed in the drag in sand casting and not in the cope. Explain why.

A simple explanation is that if they were to be placed in the cope, they would develop a high buoyancy force that would tend to separate the mold and thus develop flashes on the casting.

Problems

5.57 Referring to Fig. 5.3, estimate the following quantities for a 20% Cu-80% Ni alloy: (1) liquidus temperature, (2) solidus temperature, (3) percentage of nickel in the liquid at 1400°C (2550°F), (4) the major phase at 1400°C, and (5) the ratio of solid to liquid at 1400°C.

We estimate the following quantities from Fig. 5.3 on p. 192: (1) The liquidus temperature is 1400°C (2550°F). (2) The solidus temperature is 1372°C (2500°F). (3) At 2550°F, the alloy is still all liquid, thus the nickel concentration is 80%. (4) The major phase at 1400°C is liquid, with no solids present since the alloy is not below the liquidus temperature. (5) The ratio is zero, since no solid is present.

5.58 Determine the amount of gamma and alpha phases (see Fig. 5.4b) in a 10-kg, AISI 1060 steel casting as it is being cooled to the following temperatures: (1) 750°C, (2) 728°C, and (3) 726°C.

We determine the following quantities from Fig. 5.6 on p. 197: (a) At 750°C, the alloy is just in the single-phase austenite (gamma) region, thus the percent gamma is 100% (10 kg), and alpha is 0%. (b) At 728°C, the alloy is in the two-phase gamma-alpha field, and the weight percentages of each is found by the lever rule (see Example 5.1):

$$\begin{aligned} \%\alpha &= \left(\frac{x_\gamma - x_o}{x_\gamma - x_\alpha}\right) \times 100\% \\ &= \left(\frac{0.77 - 0.60}{0.77 - 0.022}\right) \times 100\% \\ &= 23\% \text{ or } 2.3 \text{ kg} \end{aligned}$$

$$\begin{aligned} \%\gamma &= \left(\frac{x_o - x_\alpha}{x_\gamma - x_\alpha}\right) \times 100\% \\ &= \left(\frac{0.60 - 0.022}{0.77 - 0.022}\right) \times 100\% \\ &= 77\% \text{ or } 7.7 \text{ kg} \end{aligned}$$

(c) At 726°C, the alloy is in the two-phase alpha and Fe_3C field. No gamma phase is present. Again the lever rule is used to find the amount of alpha present:

$$\%\alpha = \left(\frac{6.67 - 0.60}{6.67 - 0.022}\right) \times 100\% = 91\% \text{ or } 9.1 \text{ kg}$$

5.59 A round casting is 0.3 m in diameter and 0.5 m in length. Another casting of the same metal is elliptical in cross section, with a major-to-minor axis ratio of 3, and has the same length and cross sectional area as the round casting. Both pieces are cast under the same conditions. What is the difference in the solidification times of the two castings?

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For the same length and cross sectional area (thus the same volume), and the same casting conditions, the same C value in Eq. (5.11) on p. 205 on p. 205 should be applicable. The surface area and volume of the round casting is

$$A_{\text{round}} = 2\pi rl + 2\pi r^2 = 0.613 \text{ m}^2$$

$$V_{\text{round}} = \pi r^2 l = 0.0353 \text{ in}^2$$

Since the cross-sectional area of the ellipse is the same as that for the cylinder, and it has a major and minor diameter of a and b, respectively, where $a = 3b$, then

$$\pi ab = \pi r^2$$

$$3b^2 = r^2 \quad \rightarrow \quad b = \sqrt{\frac{(0.15)^2}{3}}$$

or $b = 0.0866$ m, so that $a = 0.260$ m. The surface area of the ellipse-based part is (see a basic geometry text for the area equation derivations):

$$A_{\text{ellipse}} = 2\pi ab + 2\pi\sqrt{a^2 + b^2}\,l = 1.002 \text{ m}^2$$

The volume is still 0.0353 in^2. According to Eq. (5.11) on p. 205, we thus have

$$\frac{T_{\text{round}}}{T_{\text{ellipse}}} = \frac{(V/A_{\text{round}})^2}{(V/A_{\text{ellipse}})^2} = \left(\frac{A_{\text{ellipse}}}{A_{\text{round}}}\right)^2 = 2.67$$

5.60 Derive Eq. (5.7).

We note that Eq. (5.5) on p. 200 gives a relationship between height, h, and velocity, v, and Eq. (5.6) on p. 201 gives a relationship between height, h, and cross sectional area, A. With the reference plate at the top of the pouring basin (and denoted as subscript 0), the sprue top is denoted as 1, and the bottom as 2. Note that h_2 is numerically greater than h_1. At the top of the sprue we have $v_o = 0$ and $h_o = 0$. As a first approximation, assume that the pressures p_o, p_1 and p_2 are equal and that the frictional loss f is negligible. Thus, from Eq. (5.5) we have

$$h_o + \frac{p_o}{\rho g} + \frac{v_o^2}{2g} = h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + f$$

or, solving for v_1,

$$0 = h_1 + \frac{v_1^2}{2g} \quad \rightarrow \quad v_1 = \sqrt{2gh_1}$$

Similarly,

$$h_o + \frac{p_o}{\rho g} + \frac{v_o^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f$$

or

$$v_2 = \sqrt{2gh_2}$$

Substituting these results into the continuity equation given by Eq. (5.6), we have

$$A_1 v_1 = A_2 v_2$$

$$A_1\sqrt{2gh_1} = A_2\sqrt{2gh_2}$$

$$\frac{A_1}{A_2} = \frac{\sqrt{2gh_2}}{\sqrt{2gh_1}} = \sqrt{\frac{h_2}{h_1}}$$

which is the desired relationship.

5.61 Two halves of a mold (cope and drag) are weighted down to keep them from separating due to the pressure exerted by the molten metal (buoyancy). Consider a solid, spherical steel casting, 9 in. in diameter, that is being produced by sand casting. Each flask (see Fig. 5.10) is 20 in. by 20 in. and 15 in. deep. The parting line is at the middle of the part. Estimate the clamping force required. Assume that the molten metal has a density of 500 lb/ft^3 and that the sand has a density of 100 lb/ft^3,

The force exerted by the molten metal is the product of its cross-sectional area at the parting line and the pressure of the molten metal due to the height of the sprue. Assume that the sprue has the same height as the cope, namely, 15 in. The pressure of the molten metal is the product of height and density. Assuming a density for the molten metal of 500 lb/ft^3, the pressure at the parting line will be $(500)(15/12) = 625$ lb/ft^2, or 4.34 psi. The buoyancy force is the product of projected area and pressure, or $(625)(\pi)(9/12)^2 = 1100$ lb. The net volume of the sand in each flask is

$$V = (20)(20)(15) - (0.5)\left(\frac{4\pi}{3}\right)(9)^3$$

or $V = 4473$ in^3 $= 2.59$ ft^3. For a sand density of 100 lb/ft^3, the cope weighs 454 lb. Under these circumstances, a clamping force of $1100 - 259 \approx 850$ lb is required.

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5.62 Would the position of the parting line in Problem 5.61 influence your answer? Explain.

The position of the parting line does have an influence on the answer to Problem 5.54, because (a) the projected area of the molten metal will be different and (b) the weight of the cope will also be different.

5.63 Plot the clamping force in Problem 5.61 as a function of increasing diameter of the casting, from 10 in. to 20 in.

Note in this problem that as the diameter of the casting increases, the cross-sectional area of the molten metal increases, hence the buoyancy force also increases. At the same time, the weight of the cope decreases because of the larger space taken up by the molten metal. Using the same approach as in Problem 5.61, the weight of the casting as a function of diameter is given by

$$\begin{aligned} F_b &= \rho V = (500)\left(\frac{\pi}{6}d^3\right) \\ &= \left(261 \text{ lb/ft}^3\right) d^3 \end{aligned}$$

The volume of sand in the cope is given by:

$$\begin{aligned} V &= (20)(20)(15)\left(\frac{1}{12}\right)^3 - (0.5)\left(\frac{\pi}{6}\right) d^3 \\ &= 3.47 \text{ ft}^3 - 0.261 d^3 \end{aligned}$$

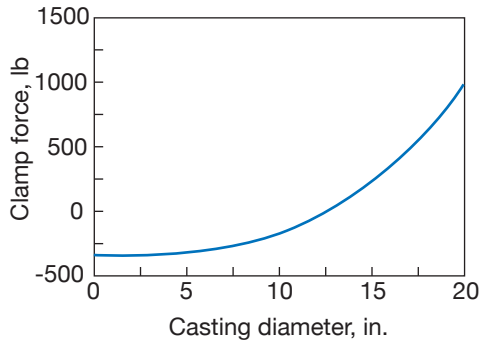
Therefore, the weight of the sand is given by:

$$\begin{aligned} F_w &= \rho_{\text{sand}} V \\ &= \left(100 \text{ lb/ft}^3\right)\left(3.47 \text{ ft}^3 - 0.261 d^3\right) \\ &= 347 \text{ lb} - \left(26.1 \text{ lb/ft}^3\right) d^3 \end{aligned}$$

The required clamping force is given by equilibrium as

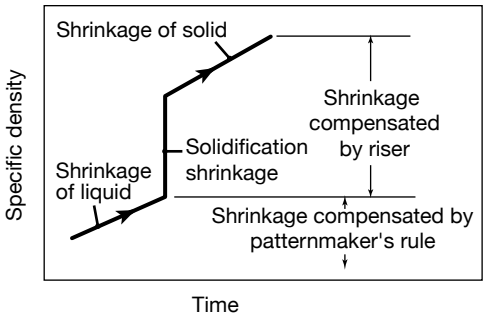
$$\begin{aligned} F_c &= F_b - F_w \\ &= \left(261 \text{ lb/ft}^3\right) d^3 - 347 \text{ lb} \\ &\quad + \left(26.1 \text{ lb/ft}^3\right) d^3 \\ &= \left(287 \text{ lb/ft}^3\right) d^3 - 347 \text{ lb} \end{aligned}$$

This equation is plotted below. Note that for a small diameter, no clamping force is needed, as the weight of the cope is sufficient to hold the cope and drag together.



5.64 Sketch a graph of specific volume vs. temperature for a metal that shrinks as it cools from the liquid state to room temperature. On the graph, mark the area where shrinkage is compensated for by risers.

The graph is as follows. See also Fig. 5.1b on p. 189.



5.65 A round casting has the same dimensions as in Problem 5.59. Another casting of the same metal is rectangular in cross-section, with a width-to-thickness ratio of 3, and has the same length and cross-sectional area as the round casting. Both pieces are cast under the same conditions. What is the difference in the solidification times of the two castings?

The castings have the same length and cross-sectional area (thus the same volume) and the same casting conditions, hence the same C value. The total surface area of the round casting, with $l = 500$ mm and $r = 150$ mm, is

$$\begin{aligned} A_{\text{round}} &= 2\pi rl + 2\pi r^2 \\ &= 2\pi(150)(500) + 2\pi(150)^2 \\ &= 6.13 \times 10^5 \text{ mm}^2 \end{aligned}$$

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The cross-sectional area of the round casting is $\pi r^2 = \pi(150)^2 = 70,680$ mm^2. The rectangular cross section has sides x and $3x$, so that

$$70,680 = 3x^2 \quad \rightarrow \quad x = 153 \text{ mm}$$

hence the perimeter of the rectangular casting with the same cross-sectional area and axes ratio of 3 is 1228 mm. The total surface area is

$$A_{\text{rect}} = 2(70,680) + (1228)(500)$$

or $A_{\text{rect}} = 7.55 \times 10^5$ mm^2. According to Chvorinov's rule, cooling time for a constant volume is inversely proportional to surface area squared. Therefore,

$$\frac{t_{\text{rect}}}{t_{round}} = \left(\frac{6.13 \times 10^5}{7.55 \times 10^5}\right)^2 = 0.66$$

5.66 A 75-mm thick square plate and a right circular cylinder with a radius of 100 mm and height of 50 mm each have the same volume. If each is to be cast using a cylindrical riser, will each part require the same size riser to ensure proper feeding of the molten metal? Explain.

Recall that it is important for the riser to solidify after the casting has solidified. A casting that solidifies rapidly would most likely require a smaller riser than one which solidifies over a longer period of time. Lets now calculate the relative solidification times, using Chvorinov's rule given by Eq. (5.11) on p. 205 on p. 205. For the cylindrical part, we have

$$V_{\text{cylinder}} = \pi r^2 h = \pi(0.1 \text{ m})^2(0.050 \text{ m})$$

or $V_{\text{cylinder}} = 0.00157$ m^3. The surface area of the cylinder is

$$\begin{aligned} A_{\text{cylinder}} &= 2\pi r^2 + 2\pi rh \\ &= 2\pi(0.1)^2 + 2\pi(0.1)(0.05) \\ &= 0.0942 \text{ m}^2 \end{aligned}$$

Thus, from Eq. (5.11) on p. 205 on p. 205,

$$t_{\text{cylinder}} = C\left(\frac{0.00157}{0.0942}\right)^2 = \left(2.78 \times 10^{-4}\right) C$$

For a square plate with sides L and height $h = 0.075$ m, and the same volume as the cylinder, we have

$$V_{\text{plate}} = 0.00157 \text{ m}^3 = L^2 h = L^2(0.075 \text{ m})$$

Solving for L yields $L = 0.144$ m. Therefore,

$$\begin{aligned} A_{\text{plate}} &= 2L^2 + 4Lh \\ &= 2(0.144)^2 + 4(0.144)(0.075) \end{aligned}$$

or $A_{\text{plate}} = 0.0847$ m^2. From Eq. (5.11) on p. 205 on p. 205,

$$t_{\text{plate}} = C\left(\frac{0.00157}{0.0847}\right)^2 = \left(3.43 \times 10^{-4}\right) C$$

Therefore, the cylindrical casting will take longer to solidify and will thus require a larger riser.

5.67 Assume that the top of a round sprue has a diameter of 4 in. and is at a height of 12 in. from the runner. Based on Eq. (5.7), plot the profile of the sprue diameter as a function of its height. Assume that the sprue has a diameter of 1 in. at its bottom.

From Eq. (5.7) on p. 201 and substituting for the area, it can be shown that

$$\frac{d_1^2}{d^2} = \sqrt{\frac{h}{h_1}}$$

Therefore,

$$d = \sqrt{d_1^2 \sqrt{\frac{h_1}{h}}} \quad \rightarrow \quad d = Ch^{-0.25}$$

The difficulty here is that the reference location for height measurements is not known. Often chokes or wells are used to control flow, but this problem will be solved assuming that proper flow is to be attained by considering hydrodynamics in the design of the sprue. The boundary conditions are that at $h = h_o$, $d = 4$ (where h_o is the height at the top of the sprue from the reference location) and at $h = h_o + 12$ in., $d = 1$ in. The first boundary condition yields

$$4 = C(h_o)^{-0.25} \quad \text{or} \quad C = 4h_o^{0.25}$$

The second boundary condition yields

$$1 = C(h_o + 12)^{-0.25} = \left(4h_o^{0.25}\right)(h_o + 12)^{-0.25}$$

This equation is solved as $h_o = 0.047$ in., so that $C = 1.863$. These values are substituted into the expression above to obtain

$$d = 1.863(h + 0.047)^{-0.25}$$

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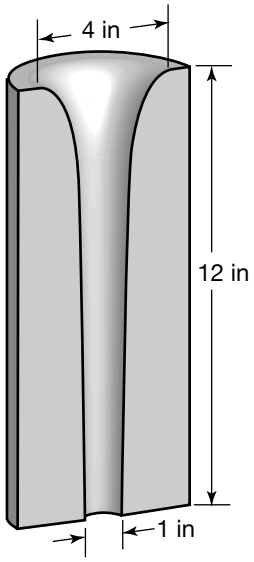
Note that h_o is the location of the bottom of the sprue and that the sprue is axisymmetric. The sprue shape, based on this curve, is shown below.



5.68 Estimate the clamping force for a diecasting machine in which the casting is rectangular, with projected dimensions of 75 mm x 150 mm. Would your answer depend on whether or not it is a hot-chamber or cold-chamber process? Explain.

The clamping force is needed to compensate for the separating force developed when the metal is injected into the die. When the die is full, and the full pressure is developed, the separating force is $F = pA$, where p is the pressure and A is the projected area of the casting. Note that the answer will depend on whether the operation is hot- or cold-chamber, because pressures are higher in the cold-chamber than in the hot-chamber process.

The projected area is 11,250 mm^2. In the hot-chamber process, an average pressure is taken as 15 MPa (see Section 5.10.3), although the pressure can range up to 35 MPa. If we use an average pressure, the required clamping force is

$$F_{\text{hot}} = pA = (35)(11,250) = 394 \text{ kN}$$

For the cold-chamber process and using a mid-range pressure of 45 MPa, the force will be

$$F_{\text{cold}} = pA = (45)(11,250) = 506 \text{ kN}$$

5.69 When designing patterns for casting, patternmakers use special rulers that automatically incorporate solid shrinkage allowances into their designs. Therefore, a 12-in. patternmaker's ruler is longer than a foot. How long should a patternmaker's ruler be for the making of patterns for (1) aluminum castings (2) malleable cast iron and (3) high-manganese steel?

It was stated in Section 5.12.2 on p. 248 that typical shrinkage allowances for metals are $\frac{1}{8}$ to $\frac{1}{4}$ in./ft, so it is expected that the ruler be around 12.125-12.25 in. long. Specific shrinkage allowances for these metals can be obtained from the technical literature or the internet. For example, from Kalpakjian, *Manufacturing Processes for Engineering Materials*, 3rd ed., p. 280, we obtain the following:

Metal	Shrinkage allowance, %
Aluminum	1.3
Malleable cast Iron	0.89
High-manganese steel	2.6

From the following formula,

$$L_{\text{ruler}} = L_o(1 + \text{shrinkage})$$

We find that for aluminum,

$$L_{\text{Al}} = (12)(1.013) = 12.156 \text{ in.}$$

For malleable cast iron,

$$L_{\text{iron}} = (12)(1.0089) = 12.107 \text{ in.}$$

and for high-manganese steel,

$$L_{\text{steel}} = (12)(1.026) = 12.312 \text{ in.}$$

Note that high-manganese steel and malleable cast iron were selected for this problem because they have extremely high and low shrinkage allowances, respectively. The aluminum ruler falls within the expected range, as do most other metals.

5.70 The blank for the spool shown in the accompanying figure is to be sand cast out of A-319, an aluminum casting alloy. Make a sketch of the wooden pattern for this part. Include all necessary allowances for shrinkage and machining.

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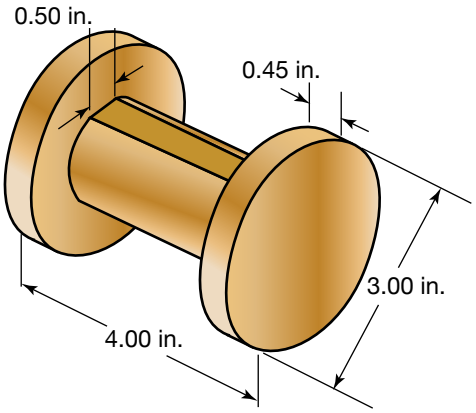
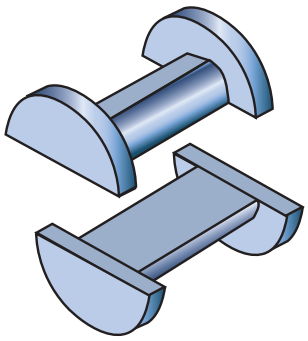
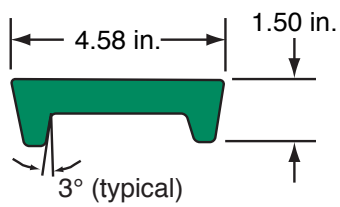


The sketch for a typical green-sand casting pattern for the spool is shown below. A cross-sectional view is also provided to clearly indicate shrinkage and machining allowances, as well as the draft angles. The important elements of this pattern are as follows (dimensions in inches):

(a) Two-piece pattern.
(b) Locating pins will be needed in the pattern plate to ensure that these features align properly.
(c) Shrinkage allowance = 5/32 in./ft.
(d) Machining allowance = 1/16 in.
(e) Draft = 3°.

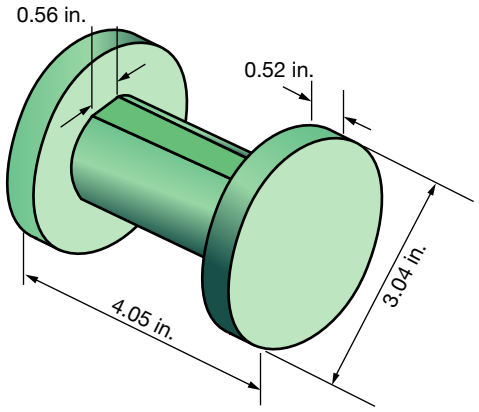




5.71 Repeat Problem 5.70, but assume that the aluminum spool is to be cast using expendable-pattern casting. Explain the important differences between the two patterns.

A sketch for a typical expandable-pattern casting is shown below. A cross-sectional view is also provided to clearly show the differences between green-sand (from Problem 5.70) and evaporative-casting patterns. There will be some variations in the patterns produced by students depending on which dimensions are assigned a machining allowance. The important elements of this pattern are as follows (dimensions in inches):

(a) One-piece pattern, made of polystyrene.
(b) Shrinkage allowance = 5/32 in./ft
(c) Machining allowance = 1/16 in.
(d) No draft angles are necessary.



5.72 In sand casting, it is important that the cope mold half be held down with sufficient force to keep it from floating when the molten metal is poured in. For the casting shown in the accompanying figure, calculate the minimum amount of weight necessary to keep the cope from floating up as the molten metal is poured in. (*Hint:* The buoyancy force exerted by the molten metal on the cope is related to the effective height of the metal head above the cope.)

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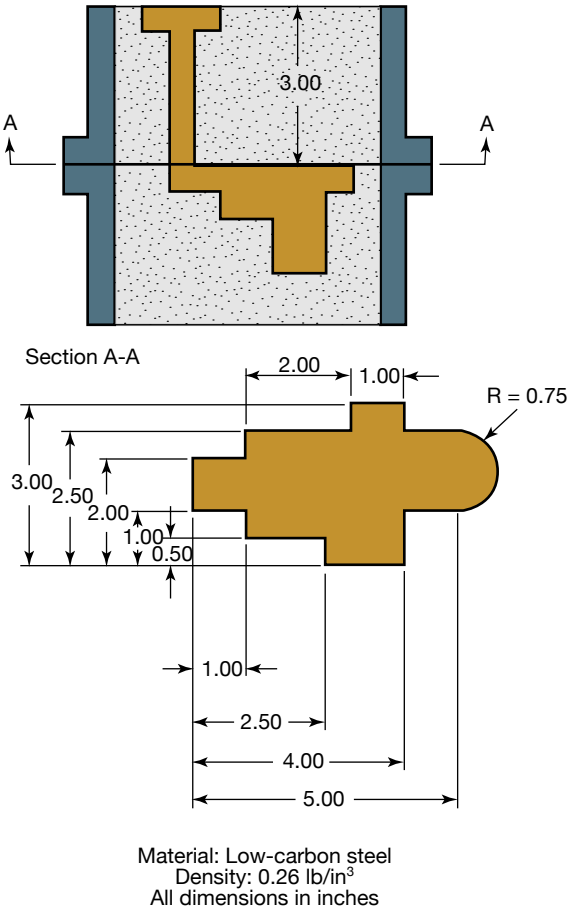


The cope mold half must be sufficiently heavy or be weighted sufficiently to keep it from floating when the molten metal is poured into the mold. The buoyancy force, F, on the cope is exerted by the metallostatic pressure (caused by the metal in the cope above the parting line) and can be calculated from the formula

$$F = pA$$

where p is the pressure at the parting line and A is the projected area of the mold cavity. The pressure is

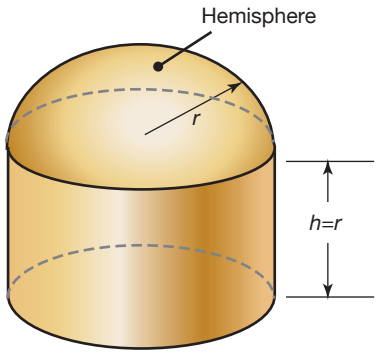
$$p = wh = (0.26 \text{ lb/in}^3)(3.00 \text{ in.}) = 0.78 \text{ psi}$$

The projected mold-cavity area can be calculated from the dimensions given on cross section AA in the problem, and is found to be 10.13 in^2. Thus, the force is

$$F = (0.78)(10.13) = 7.9 \text{ lb}$$

5.73 The optimum shape of a riser is spherical to ensure that it cools more slowly than the casting it feeds. Spherically shaped risers, however, are difficult to cast. (1) Sketch the shape of a blind riser that is easy to mold, but also has the smallest possible surface area-to-volume ratio. (2) Compare the solidification time of the riser in part (a) to that of a riser shaped like a right circular cylinder. Assume that the volume of each riser is the same, and that for each the height is equal to the diameter (see Example 5.2).

A sketch of a blind riser that is easy to cast is shown below, consisting of a cylindrical and a hemispherical portions.



Note that the height of the cylindrical portion is equal to its radius (so that the total height of the riser is equal to its diameter). The volume, V, of this riser is

$$V = \pi r^2 h + \frac{1}{2}\left(\frac{4\pi r^3}{3}\right) = \frac{5\pi r^3}{3}$$

Letting V be unity, we have

$$r = \left(\frac{3}{5\pi}\right)^{1/3}$$

The surface area of the riser is

$$A = 2\pi rh + \pi r^2 + \frac{1}{2}\left(4\pi r^2\right) = 5\pi r^2$$

Substituting for r, we obtain $A = 5.21$. Therefore, from Eq. (5.11) on p. 205, the solidification time, t, for the blind riser will be

$$t = C\left(\frac{V}{A}\right)^2 = C\left(\frac{1}{5.21}\right)^2 = 0.037C$$

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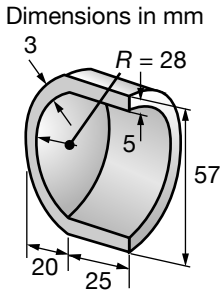
From Example 5.2, we know that the solidification time for a cylinder with a height equal to its diameter is $0.033C$. Thus, this blind riser will cool a little slower, but not much so, and is easier to cast.

5.74 The part shown in the accompanying figure is a hemispherical shell used as an acetabular (mushroom shaped) cup in a total hip replacement. Select a casting process for this part and provide a sketch of all patterns or tooling needed if it is to be produced from a cobalt-chrome alloy.



This is an industrially-relevant problem, as this is the casting used as acetabular cups for total hip replacements. There are several possible answers to this question, depending on the student's estimates of production rate and equipment costs. In practice, this part is produced through an investment casting operation, where the individual parts with runners are injection molded and then attached to a central sprue. The tooling that would be required include: (1) a mold for the injection molding of wax into the cup shape. (2) Templates for placement of the cup shape onto the sprue, in order to assure proper spacing for even, controlled cooling. (3) Machining fixtures. It should be noted that the wax pattern will be larger than the desired casting, because of shrinkage as well as the incorporation of a shrinkage allowance.

5.75 A cylinder with a height-to-diameter ratio of unity solidifies in four minutes in a sand casting operation. What is the solidification time if the cylinder height is doubled? What is the time if the diameter is doubled?

From Chvorinov's rule, given by Eq. (5.11) on p. 205, and assuming $n = 2$ gives

$$\begin{aligned} t &= C\left(\frac{V}{A}\right)^2 \\ &= C\left[\frac{(\pi d^2 h/4)}{(\pi d^2/2 + \pi dh)}\right] \\ &= C\left(\frac{dh}{2d+4h}\right) = 4 \text{ min} \end{aligned}$$

Solving for C,

$$C = (4 \text{ min})\left(\frac{2d+4h}{dh}\right)$$

If the height is doubled, then we can use $d_2 = d$ and $h_2 = 2h$ to obtain

$$\begin{aligned} t &= C\left(\frac{d_2 h_2}{2d_2 + 4h_2}\right) \\ &= (4 \text{ min})\left(\frac{2d+4h}{dh}\right)\left(\frac{d(2h)}{2d+4(2h)}\right) \\ &= (4 \text{ min})\left(\frac{4d+8h}{2d+8h}\right) \end{aligned}$$

If $d = h$, then

$$t = (4 \text{ min})\left(\frac{12h}{10h}\right) = 4.8 \text{ min}$$

If the diameter is doubled, so that $d_3 = 2d$ and $h_3 = h$, then

$$\begin{aligned} t &= C\left(\frac{d_3 h_3}{2d_3 + 4h_3}\right) \\ &= (4 \text{ min})\left(\frac{2d+4h}{dh}\right)\left(\frac{(2d)(h)}{2(2d)+4(h)}\right) \\ &= (4 \text{ min})\left(\frac{4d+8h}{4d+4h}\right) \end{aligned}$$

or, for $d = h$,

$$t = (4 \text{ min})\left(\frac{12h}{8h}\right) = 6 \text{ min}$$

5.76 Steel piping is to be produced by centrifugal casting. The length is 12 feet, the diameter is 3 ft, and the thickness is 0.5 in. Using basic equations from dynamics and statics, determine the rotational speed needed to have the centripetal force be 70 times its weight.

The centripetal force can be obtained from an undergraduate dynamics textbook as

$$F_c = \frac{mv^2}{r}$$

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where m is the mass, v is the tangential velocity, and r is the radius. It is desired to have this force to be 70 times its weight, or

$$70 = \frac{F_c}{W} = \frac{mv^2/r}{mg} = \frac{v^2}{rg}$$

since r is the mean radius of the casting, or 1.25 ft, v can be solved as

$$v = \sqrt{(70)rg} = \sqrt{(70)(1.25)(32.2)}$$

or $v = 53$ ft/sec or 637 in./sec. The rotational speed needed to obtain this velocity is

$$\omega = \frac{v}{r} = \frac{53 \text{ ft/sec}}{1.25 \text{ ft}} = 42.4 \text{ rad/sec}$$

This is equivalent to 405 rev/min.

5.77 A sprue is 12 in. long and has a diameter of 5 in. at the top, where the metal is poured. The molten metal level in the pouring basin is taken as 3 in. from the top of the sprue for design purposes. If a flow rate of 40 in^3/s is to be achieved, what should be the diameter of the bottom of the sprue? Will the sprue aspirate? Explain.

Assuming the flow is frictionless, the velocity of the molten metal at the bottom of the sprue ($h = 12$ in. $= 1$ ft) is

$$v = \sqrt{2gh} = \sqrt{2(32.2)(1)}$$

or $v = 8.0$ ft/s $= 96$ in./s. For a flow rate of 40 in^3/s, the area needs to be

$$A = \frac{Q}{v} = \frac{40 \text{ in}^3/\text{s}}{96 \text{ in./s}} = 0.417 \text{ in}^2$$

For a circular runner, the diameter would then be 0.73 in., or roughly $\frac{3}{4}$ in. Compare this to the diameter at the bottom of the sprue based on Eq. (5.7), where $h_1 = 3$ in., $h_2 = 15$ in., and $A_1 = 19.6$ in^2. The diameter at the bottom of the sprue is calculated from:

$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}$$

$$A_2 = \frac{A_1}{\sqrt{h_2/h_1}} = \frac{19.6}{\sqrt{15/3}} = 8.8 \text{ in}^2$$

$$d = \sqrt{\frac{4}{\pi}A_2} = 3.34 \text{ in}$$

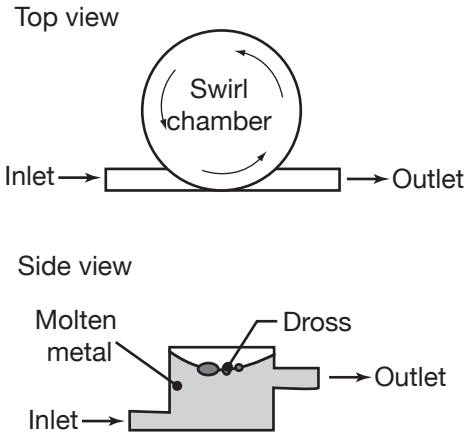
Thus, the sprue confines the flow more than is necessary, and it will not aspirate.

5.78 Small amounts of slag often persist after skimming and are introduced into the molten metal flow in casting. Recognizing that the slag is much less dense than the metal, design mold features that will remove small amounts of slag before the metal reaches the mold cavity.

There are several dross-trap designs in use in foundries. (A good discussion of trap design is given in J. Campbell, *Castings*, 1991, Reed Educational Publishers, pp. 53-55.) A conventional and effective dross trap is illustrated below:

It designed on the principle that a trap at the end of a runner will take the metal through the runner and keep it away from the gates. The design shown is a wedge-type trap. Metal entering the runner contacts the wedge, and the leading front of the metal wave is chilled and attaches itself to the runner wall, and thus it is kept out of the mold cavity. The wedge must be designed so as to avoid reflected waves that otherwise would recirculate the dross or the slag.

The following design is a swirl trap:



This is based on the principle that the dross or slag is less dense than the metal. The metal enters the trap off of the center, inducing a swirl in the molten metal as the trap fills with molten metal. Because it is far less dense than the metal, the dross or slag remains in the center of

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the swirl trap. Since the metal is tapped from the outside periphery, dross or slag is excluded from the casting.

5.79 Pure aluminum is being poured into a sand mold. The metal level in the pouring basin is 10 in. above the metal level in the mold, and the runner is circular with a 0.4 in. diameter. What is the velocity and rate of the flow of the metal into the mold? Is the flow turbulent or laminar?

Equation (5.5) on p. 200 gives the metal flow. Assuming the pressure does not change appreciably in the channel and that there is no friction in the sprue, the flow is

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g}$$

Where the subscript 1 indicates the top of the sprue and 2 the bottom. If we assume that the velocity at the top of the sprue is very low (as would occur with the normal case of a pouring basin on top of the sprue with a large cross-sectional area), then $v_1 = 0$. The velocity at the bottom of the sprue is

$$v_2^2 = 2g(h_1 - h_2)$$

or

$$v_2 = \sqrt{2g\Delta h} = \sqrt{2(32.2 \text{ ft/s}^2)(12 \text{ in/ft})(10 \text{ in})}$$

or $v_2 = 87.9$ in./s. If the opening is 0.4-in. in diameter, the area is

$$A = \frac{\pi}{4}d^2 = \frac{\pi}{4}(0.4)^2 = 0.126 \text{ in}^2$$

Therefore, the flow rate is

$$Q = v_2 A = (87.9)(0.126) = 11.0 \text{ in}^3/\text{s}.$$

Pure aluminum has a density of 2700 kg/m^3 (see Table 3.3) and a viscosity of around 0.0015 Ns/m^2 around 700°C. The Reynolds number, from Eq. (5.10) on p. 202, is then (using v = 87.9 in/s = 2.23 m/s and D = 0.4 in.=0.01016 m),

$$\begin{aligned} \text{Re} &= \frac{vD\rho}{\eta} \\ &= \frac{(2.23 \text{ m/s})(0.01016 \text{ m})(2700 \text{ kg/m}^3)}{0.0015 \text{ Ns/m}^2} \end{aligned}$$

or Re= 40,782. As discussed in Section 5.4.1 starting on p. 199, this situation would represent turbulence, and the velocity and/or diameter should be decreased to bring Re below 20,000 or so.

5.80 For the sprue described in Problem 5.79, what runner diameter is needed to ensure a Reynolds number of 2000? How long will a 20 in^3 casting take to fill with such a runner?

Using the data given in Problem 5.79, a Reynolds number of 2000 can be achieved by reducing the channel diameter, so that

$$\text{Re} = 2000 = \frac{vD\rho}{\eta} = \frac{(2.23)(2700)}{0.0015}D$$

or $D = 0.000498$ m $= 0.0196$ in.

For this diameter, the initial flow rate would be

$$\begin{aligned} Q &= v_2 A = \frac{\pi v_2}{4}D^2 = \frac{\pi}{4}(87.9)(0.0196)^2 \\ &= 0.0266 \text{ in}^3/\text{sec} \end{aligned}$$

This means that a 20 in^3 casting would take 753 s (about 12 min) to fill and only if the initial flow rate could be maintained, which is generally not the case. Such a long filling time is not acceptable, since it is likely that metal will solidify in runners and thus not fill the mold completely. Also, with such small a small runner, additional mechanisms need to be considered. For example, surface tension and friction would severely reduce the velocity in the Reynolds number calculation above.

This is generally the case with castings; to design a sprue and runner system that maintains laminar flow in the fluid would result in excessively long fill times.

5.81 How long would it take for the sprue in Problem 5.79 to feed a casting with a square cross-section of 6 in. per side and a height of 4 in.? Assume the sprue is frictionless.

Note that the volume of the casting is 144 in^3, with a constant cross-sectional area of 36 in^2. The velocity will change as the mold fills, because the pouring basin height above the molten metal will decrease. The velocity will vary according to:

$$v = c\sqrt{2gh} = \sqrt{2gh}$$

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The flow rate is given by

$$Q = vA = \frac{v\pi d^2}{4} = \frac{\pi d^2\sqrt{2gh}}{4}$$

The mold cavity fills at a rate of Q/(36 in^2), or

$$\frac{dh}{dt} = \frac{Q}{A} = -\frac{\pi d^2\sqrt{2gh}}{4A}$$

where the minus sign has been added so that h refers to the height difference between the metal level in the mold and the runner, which decreases with respect to time. Separating the variables,

$$\frac{dh}{\sqrt{h}} = -\frac{\pi d^2\sqrt{2g}}{4A}dt$$

Integrating,

$$\left(2\sqrt{h}\right)_{10\text{in}}^{6\text{in}} = -\frac{\pi d^2\sqrt{2g}}{4A}(t)_0^t$$

From this equation and using d=0.4 in. and $A = 36$ in^2, t is found to be 14.7 s. As a comparison, using the flow rate calculated in Problem 5.79, the mold would require approximately 13 s to fill.

5.82 A rectangular mold with dimensions 100 mm × 200 mm × 400 mm is filled with aluminum with no superheat. Determine the final dimensions of the part as it cools to room temperature. Repeat the analysis for gray cast iron.

Note that the initial volume of the box is (0.100)(0.200)(0.400)=0.008 m^3. From Table 5.1 on p. 206, the volumetric contraction for aluminum is 6.6%. Therefore, the box volume will be

$$V = (1 - 0.066)(0.008\text{ m}^3) = 0.007472\text{ m}^3$$

Assuming the box has the same aspect ratio as the mold (1:2:4) and that warpage can be ignored, we can calculate the dimensions of the box after solidification as 97.7 mm × 195.5 mm × 391 mm. From Table 3.3 on p. 106, the melting point of aluminum is 660°C, with a coefficient of thermal expansion of 23.6 μm/m°C. Thus, the total strain in cooling from 660°C to room temperature (25°C) is

$$\epsilon = \alpha\Delta t = (23.6\mu\text{m/m}^\circ\text{C})(660^\circ\text{C} - 25^\circ\text{C})$$

or $\epsilon = 0.0150$. The final box dimensions are therefore 96.2 × 192.5 × 385 mm.

For gray cast iron, the metal expands upon solidification. Assuming the mold will allow for expansion, the volume after solidification is given by

$$V = (1.025)(0.008\text{ m}^3) = 0.0082\text{ m}^3$$

If the box has the same aspect ratio as the initial mold cavity, the dimensions after solidification will be 100.8 × 201.7 × 403.3 mm. Using the data for iron in Table 3.3, the melting point is taken as 1537°C and the coefficient of thermal expansion as 11.5 μm/m°C. Therefore,

$$\epsilon = \alpha\Delta t = (11.5\mu\text{m/m}^\circ\text{C})(1537^\circ\text{C} - 25^\circ\text{C})$$

or $\epsilon = 0.0174$. Hence, the final dimensions are 99.0 × 198.1 × 396 mm. Note that even though the cast iron had to cool off from a higher initial temperature, the box of cast iron is much closer to the mold dimensions than the aluminum.

5.83 The constant C in Chvorinov's rule is given as 3 s/mm^2 and is used to produce a cylindrical casting with a diameter of 75 mm and a height of 125 mm. Estimate the time for the casting to fully solidify. The mold can be broken safely when the solidified shell is at least 20 mm. Assuming the cylinder cools evenly, how much time must transpire after pouring the molten metal before the mold can be broken?

Note that for the cylinder

$$\begin{aligned} A &= 2\left(\frac{\pi}{4}d^2\right) + \pi dh \\ &= 2\left[\frac{\pi}{4}(75)^2\right] + \pi(75)(125) \\ &= 38,290\text{ mm}^2 \end{aligned}$$

$$V = \frac{\pi}{4}d^2h = \frac{\pi}{4}(75)^2(125) = 5.522\times10^5\text{ mm}^3$$

From Chvorinov's rule given by Eq. (5.11) on p. 205,

$$t = C\left(\frac{V}{A}\right)^2 = (3\text{ s/mm}^2)\left(\frac{5.522\times10^5}{38,290}\right)^2$$

or $t = 624$ s, or just over 10 min to solidify.

The second part of the problem is far more difficult, and different answers can be obtained depending on the method of analysis. The solution is not as straightforward as it may seem initially. For example, one could say that

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the 20 mm wall is 53.3% of the thickness, so that 0.533(624)=333 s is needed. However, this would not be sufficient because an annular section at an outside radius has more material than one closer to the center. It is thus reasonable and conservative to consider the time required for the remaining cylinder to solidify. Using $h = 85$ mm and $d = 35$ mm, the solidification time is found to be 21.8 s. Therefore, one still has to wait 602 s before the mold can be broken.

5.84 If an acceleration of 100 g is necessary to produce a part in true centrifugal casting and the part has an inner diameter of 10 in., a mean outer diameter of 14 in., and a length of 25 ft., what rotational speed is needed?

The angular acceleration is given by $\alpha = \omega^2 r$. Recognizing that the largest force is experienced at the outside radius, this value for r is used in the calculation:

$$\alpha = \omega^2 r = 100 \text{ g} = 3220 \text{ ft/s}^2$$

Therefore, solving for ω,

$$\omega = \sqrt{\alpha / r} = \sqrt{\left(3220 \text{ ft/s}^2\right) / (0.583 \text{ ft})}$$

or $\omega = 74$ rad/s $= 710$ rpm.

5.85 A jeweler wishes to produce twenty gold rings in one investment-casting operation. The wax parts are attached to a wax central sprue of a 0.5 in. diameter. The rings are located in four rows, each 0.5 in. from the other on the sprue. The rings require a 0.125-in. diameter and 0.5-in. long runner to the sprue. Estimate the weight of gold needed to completely fill the rings, runners, and sprues. The specific gravity of gold is 19.3.

The particular answer will depend on the geometry selected for a typical ring. Let's approximate a typical ring as a tube with dimensions of 1 in. outer diameter, 5/8 in. inner diameter, and 3/8 in. width. The volume of each ring is then 0.18 in^3, and a total volume for 20 rings of 3.6 in^3. There are twenty runners to the sprue, so this volume component is

$$V = 20\left(\frac{\pi}{4}d^2\right)L = 20\left(\frac{\pi}{4}(0.125 \text{ in.})^2\right)(0.5 \text{ in.})$$

or $V = 0.123$ in^3. The central sprue has a length of 1.5 in., so that its volume is

$$V = \frac{\pi}{4}d^2 L = \frac{\pi}{4}(0.5 \text{ in.})^2(1.5 \text{ in.}) = 0.29 \text{ in}^3$$

The total volume is then 4.0 in^3, not including the metal in the pouring basin, if any. The specific gravity of gold is 19.3, thus its density is $19.3(62.4 \text{ lb/ft}^3) = 0.697 \text{ lb/in}^3$. Therefore, the jeweler needs 2.79 lb. of gold.

5.86 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

Design

5.87 Design test methods to determine the fluidity of metals in casting (see Section 5.4.2 starting on p. 203). Make appropriate sketches and explain the important features of each design.

By the student. The designs should allow some method of examining the ability of a metal to fill the mold. One example, taken from Kalpakjian and Schmid, *Manufacturing Engineering and Technology*, 5th ed, Prentice-Hall, 2001, is shown below.

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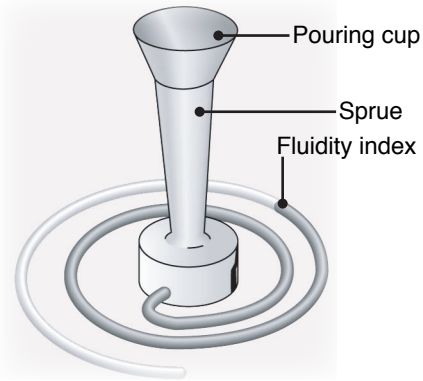
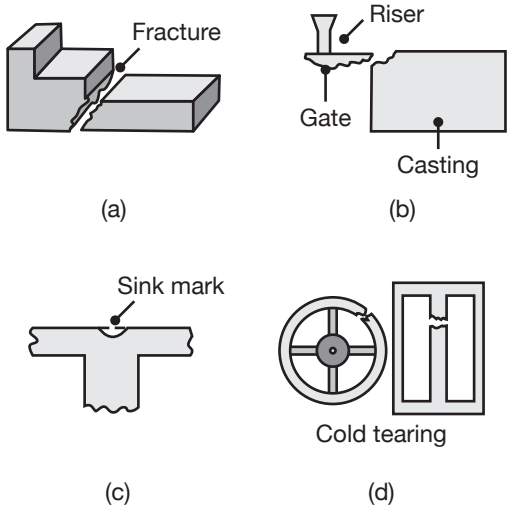


5.88 The accompanying figures indicate various defects and discontinuities in cast products. Review each one and offer design solutions to avoid them.



By the student. Some examples are for (a) fracture is at stress raiser, a better design would utilize a more gradual filet radius; (b) fracture at the gate indicates this runner section is too narrow and thus it solidified first, hence the gate should be larger.

5.89 Utilizing the equipment and materials available in a typical kitchen, design an experiment to reproduce results similar to those shown in Fig. 5.12.

A simple experiment can be performed with melted chocolate and a coffee cup. If a parting agent is sprayed into the cup, and molten chocolate is poured, after a short while the still molten center portion can be poured from the cup, leaving a solidified shell. This effect can be made more pronounced by using chilling the cups first.

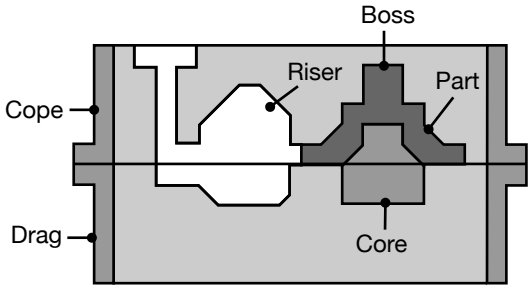
5.90 Design a test method to measure the permeability of sand for sand casting.

Permeability suggests that there is a potential for material to penetrate somewhat into the porous mold material. The penetration can be measured through experimental setups, such as using a standard-sized slug or shape of sand, applying a known pressure to one side, and then measuring the flow rate through the sand.

5.91 Describe the procedures that would be involved in making a bronze statue. Which casting process or processes would be suitable? Why?

The answer depends on the size of the statue. A small statue (say 100 mm tall) can be die cast if the quantities desired are large enough, or it can be sand cast for fewer quantities. The very large statues such as those found in public parks, which typically are on the order of 1 to 3 m tall, are produced by first manufacturing or sculpting a blank from wax and then using the investment-casting process. Another option for a large casting is to carefully prepare a ceramic mold.

5.92 Porosity developed in the boss of a casting is illustrated in the accompanying figure. Show that by simply repositioning the parting line of this casting, this problem can be eliminated.



Note in the figure that the boss is at some distance from the blind riser. Consequently, the boss can develop porosity (not shown in the figure, but to be added by the instructor) because of a lack of supply of molten metal from the

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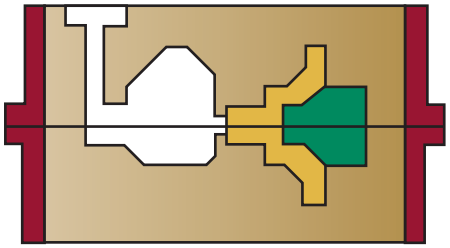
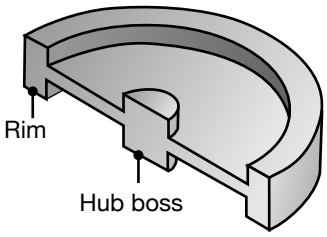
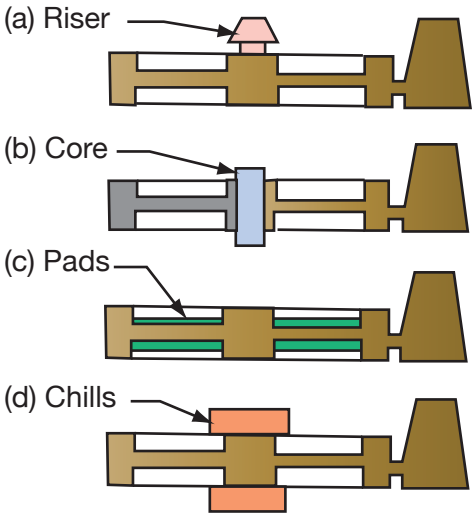
riser. The sketch below shows a repositioned parting line that would eliminate porosity in the boss. Note in the illustration below that the boss can now be supplied with molten metal as it begins to solidify and shrink.



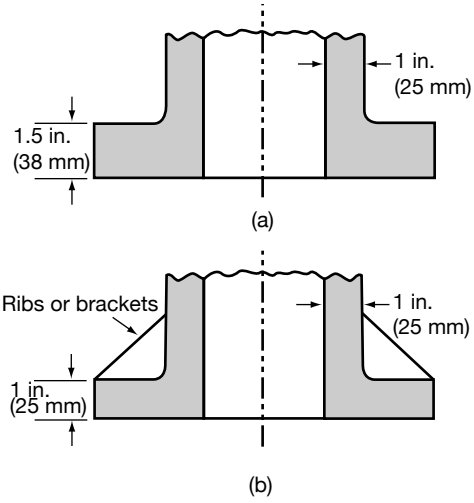
5.93 For the wheel illustrated in the accompanying figure, show how (a) riser placement, (b) core placement, (c) padding, and (d) chills may be used to help feed molten metal and eliminate porosity in the isolated hob boss.



Four different methods are shown below.

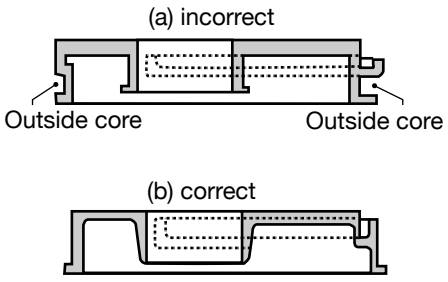


5.94 In the figure below, the original casting design shown in (a) was changed to the design shown in (b). The casting is round, with a vertical axis of symmetry. As a functional part, what advantages do you think the new design has over the old one?



By the student. There are several advantages, including that the part thickness is more uniform, so that large shrinkage porosity is less likely, and the ribs will control warping due to thermal stresses as well as increasing joint stiffness.

5.95 An incorrect and a correct design for casting are shown, respectively, in the accompanying figure. Review the changes made and comment on their advantages.



By the student. The main advantage of the new design is that it can be easily cast without the need for an external core. The original part would require two such cores, because the geometry is such that it cannot be obtained in a sand mold without cores.

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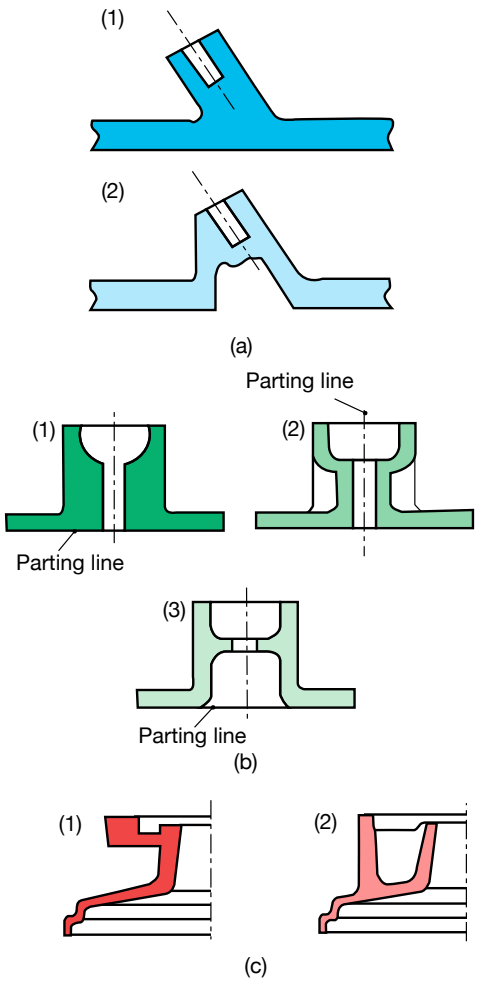
5.96 Three sets of designs for die casting are shown in the accompanying figure. Note the changes made to original die design (number 1 in each case) and comment on the reasons.



By the student. There are many observations, usually with the intent of minimizing changes in section thickness, eliminating inclined surfaces to simplify mold construction, and to orient flanges so that they can be easily cast.

5.97 It is sometimes desirable to cool metals more slowly than they would be if the molds were maintained at room temperature. List and explain the methods you would use to slow down the cooling process.

There can be several approaches to this problem, including:

- Heated molds will maintain temperatures higher than room temperature, but will still allow successful casting if the mold temperature is below the melting temperature of the metal.
- The mold can be placed in a container; heat from the molten metal will then warm the local environment above room temperature.
- The mold can be insulated to a greater extent, so that its steady-state temperature is higher (permanent-mold processes).
- The mold can be heated to a higher temperature.
- An exothermic jacket can be placed around the molten metal.
- Radiation heat sources can be used to slow the rate of heat loss by conduction.

5.98 Design an experiment to measure the constants C and n in the Chvorinov's Rule [Eq. (5.11)].

The following are some tests that could be considered:

- The most straightforward tests involve producing a number of molds with a family of parts (such as spheres, cubes or cylinders with a fixed length-to-diameter ratio), pouring them, and then breaking the mold periodically to observe if the metal has solidified. This inevitably results in spilled molten metal and may therefore a difficult test procedure to use.
- Students should consider designing molds that are enclosed but have a solidification front that terminates at an open riser; they can then monitor the solidification times can then be monitored, and then determine fit Eq. (5.11) on p. 205 to their data.
- An alternative to solidifying the metal is to melt it within a mold specially designed for such an experiment.

5.99 The part in the accompanying figure is to be cast of 10% Sn bronze at the rate of 100 parts per month. To find an appropriate casting process, consider all the processes in this chapter, then reject those that are (a) technically inadmissible, (b) technically feasible but too expensive for the purpose, and (c) identify the

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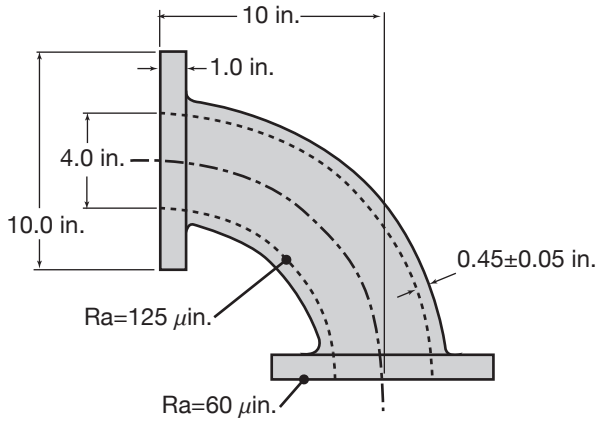
most economical process. Write a rationale using common-sense assumptions about product cost.



The answers could be somewhat subjective, because the particular economics are affected by company capabilities and practices. The following summary is reasonable suggestion:

Process	Note	Cost rationale
Sand casting		This is probably best.
Shell-mold casting	(a)	
Lost Foam		Need tooling to make blanks. Too low of production rate to justify.
Plaster mold	(a)	
Ceramic mold	(b)	
Lost Wax		Need to make blanks. Too low of production rate to justify, unless rapid tooling is used.
Vacuum casting	(b)	
Pressure casting	(b)	
Die casting	(b)	
Centrifugal casting	(b)	
CZ Process	(b)	

Notes: (a) technically inadmissible; (b) Too expensive.

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Chapter 6

Bulk Deformation Processes

Questions

Forging

6.1 How can you tell whether a certain part is forged or cast? Describe the features that you would investigate to arrive at a conclusion.

Numerous tests can be used to identify cast vs. forged parts. Depending on the forging temperature, forged parts are generally tougher than cast parts, as can be verified when samples from various regions of the part are subjected to a tensile test. Hardness comparisons may also be made. Microstructures will also indicate forged vs. cast parts. Grain size will usually be smaller in forgings than in castings, and the grains will undergo deformation in specific directions (preferred orientation). Cast parts, on the other hand, will generally be more isotropic than forged parts. Surface characteristics and roughness are also likely to be different, depending on the specific casting processes used and the condition of the mold or die surfaces.

6.2 Why is the control of volume of the blank important in closed-die forging?

If too large of a blank is placed into the dies in a closed-die forging operation, presses will (a) jam, (b) not complete their stroke, and (c) subject press structures to high loads. Numerous catastrophic failures in C-frame presses have been attributed to such excessive loads. If, on the other hand, the blank is too small, the desired shape will not be completely imparted onto the workpiece.

6.3 What are the advantages and limitations of a cogging operation? Of die inserts in forging?

Because the contact area in cogging is much smaller (incremental deformation) than in a regular forging operation, large sections of bars can be reduced at much low loads, thus requiring lower-capacity machinery, which is an important economic advantage. Furthermore, various cross sections can be produced along the length of the bar by varying the strokes during cogging. A corresponding disadvantage is the time and large number of strokes required to cog long workpieces, as well as the difficulty in controlling deformation with sufficient dimensional accuracy and surface finish.

6.4 Explain why there are so many different kinds of forging machines available.

Each type of forging machine has its own advantages and limitations, each being ideally suited for different applications. Major factors involved in equipment selection may be summarized as follows:

(a) Force and energy requirements,

(b) Force-stroke characteristics,

(c) Length of ram travel,

(d) Production rate requirements,

(e) Strain-rate sensitivity of the workpiece materials,

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(f) Cooling of the workpiece in the die in hot forging, and its consequences regarding die filling and forging forces,

(g) Economic considerations.

6.5 Devise an experimental method whereby you can measure the force required for forging only the flash in impression-die forging. (See Fig. 6.15a.)

An experimental method to determine the forces required to forge only the flash (for an axisymmetric part) would involve making the die in two concentric pieces, each with its own load cell to measure the force. The die in the center would only cover the projected area of the part itself, and the outer die (ring shaped) would cover the projected area of the annular flash. During forging, the load cells are monitored individually and, thus, the loads for the part and the flash, respectively, can be measured independently. Students are encouraged to devise other possible and practical methods.

6.6 A manufacturer is successfully hot forging a certain part, using material supplied by Company A. A new supply of material is obtained from Company B, with the same nominal composition of the major alloying elements as that of the material from Company A. However, it is found that the new forgings are cracking even though the same procedure is followed as before. What is the probable reason?

The probable reason is the presence of impurities, inclusions, and minor elements (such as sulfur) in the material supplied by Company B. Note that the question states that both materials have the "same nominal composition of the major alloying elements". No mention is made regarding minor elements or impurity levels.

6.7 Explain why there might be a change in the density of a forged product as compared to that of the cast blank.

If the original material has porosity, such as from a poor casting with porosity due to gases or shrinkage cavities, its density will increase after forging because the pores will close under the applied compressive stresses. On the other hand, the original blank may be free of any porosity but due to adverse material flow and state of stress during plastic deformation, cavities may develop (similar to voids that develop in the necked region of a tensile-test specimen, see Fig. 3.24 on p. 100). Thus, the density will decrease after forging due to void formation.

6.8 Since glass is a good lubricant for hot extrusion, would you use glass for impression-die forging as well? Explain.

Glass, in various forms, is used for hot forging operations. However, in impression-die forging, even thin films (because glass is incompressible) will prevent the part from producing the die geometry, and thus develop poor quality, and may prevent successful forging of intricate shapes. If the glass lubricant solidifies in deep recesses of the dies, they will be difficult and costly to remove.

6.9 Describe and explain the factors that influence spread in cogging operations on square billets.

A review of the events taking place at the die-workpiece interface in cogging indicates that the factors that influence spreading are:

(a) Friction: the lower the friction, the more the spreading because of reduced lateral resistance to material flow.

(b) Width-to-thickness ratio of the workpiece: the higher this ratio, the lower the spreading.

(c) Contact length (in the longitudinal direction)-to-workpiece ratio); the higher this ratio, the higher the spreading. Recall that the material flows in the direction of least resistance.

6.10 Why are end grains generally undesirable in forged products? Give examples of such products.

As discussed in Section 6.2.5 starting on p. 283, end grains are generally undesirable because corrosion occurs preferentially along grain boundaries. Thus end grains present many grain boundaries at the surface for corrosion to take place. In addition, they may result in objectionable surface appearance, as well as reducing the fatigue life of the component because of surface roughness that results from corrosion.

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6.11 Explain why one cannot produce a finished forging in one press stroke, starting with a blank.

Forgings are typically produced through a series of operations, such as edging, blocking, etc., as depicted in Fig. 6.25 on p. 285. This is done for a number of reasons:

(a) The force and energy requirements on the press are greatly reduced by performing the operations sequentially;

(b) The part may have to be subjected to intermediate annealing, thus allowing less ductile materials to be forged to complicated shapes.

(c) Reviewing the Archard wear law given by Eq. (4.6) on p. 145, it can be seen that low die wear rates can be achieved if the sliding distance and/or the force is low in a stroke. Reviewing Fig. 6.25 on p. 285, it can be seen that each operation will involve a large sliding distance between the workpiece and dies, thus causing more wear.

6.12 List the advantages and disadvantages of using a lubricant in forging operations.

The advantages include:

(a) a reduction in the force and energy required;

(b) less localization of strain, resulting in improved forgeability;

(c) the lubricant acts as a thermal barrier, so that the part can remain hotter longer and thus have more ductility;

(d) the lubricant can protect the workpiece from the environment, especially in hot forging, and also act as a parting agent.

The disadvantages include:

(a) The lubricant adds cost to the operation;

(b) a thick film can result in orange-peel effect on the workpiece;

(c) lubricants may be entrapped in die cavities, thus part dimensions my not be acceptable;

(d) the lubricant must subsequently be removed from the part surface, an additional and difficult operation;

(e) disposal of the lubricant can present environmental shortcomings.

6.13 Explain the reasons why the flash assists in die filling, especially in hot forging.

The flash is excess metal which is squeezed out from the die cavity into the outer space between the two dies. The flash cools faster than the material in the cavity due to the high a/h ratio and the more intimate contact with the relatively cool dies. Consequently, the flash has higher strength than the hotter workpiece in the die cavity and, with higher frictional resistance in the flash gap, provides greater resistance to material flow outward through the flash gap. Thus, the flash encourages filling of complex die cavities.

6.14 By inspecting some forged products (such as a pipe wrench or coins), you can see that the lettering on them is raised rather than sunk. Offer an explanation as to why they are made that way.

By the student. It is much easier and economical to machine cavities in a die (thus producing lettering on a forging that are raised from its surface) than producing protrusions (thus producing lettering that are like impressions on the forged surface). Note that to produce a protrusion on the die, material surrounding the letters be removed, a difficult operation for most lettering. Recall also similar consideration in cast products.

Rolling

6.15 It was stated that three factors that influence spreading in rolling are (a) the width-to-thickness ratio of the strip, (b) friction, and (c) the ratio of the radius of the roll to the thickness of the strip. Explain how each of these factors affects spreading.

These parameters basically all contribute to the frictional resistance in the width direction of the strip by changing the aspect ratio of the contact area between the roll and the strip (see also Answer 6.9 above).

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6.16 Explain how you would go about applying front and back tensions to sheet metals during rolling.

Front tensions are applied and controlled by the take-up reel of a rolling mill; the higher the torque to this reel or the higher the rotational speed, the greater the front tension. Back tension is applied by the pay-off reel by increasing the braking torque on the pay-off reel or reducing its rotational speed.

6.17 It was noted that rolls tend to flatten under roll forces. Which property(ies) of the roll material can be increased to reduce flattening? Why?

Flattening is elastic deformation of the originally circular roll cross section, and results in a larger contact length in the roll gap. Therefore, the elastic modulus of the roll should be increased.

6.18 Describe the methods by which roll flattening can be reduced.

Roll flattening can be reduced by:

(a) decreasing the reduction per pass,
(b) reducing friction, and/or
(c) increasing the roll stiffness (for example, by making it from materials with high modulus of elasticity, such as carbides).

6.19 Explain the technical and economic reasons for taking larger rather than smaller reductions per pass in flat rolling.

Economically, it is always beneficial to reduce the number of operations involved in manufacturing of products. Reducing the number of passes in rolling achieves this result by lowering the number of required operations. This allows less production time to achieve the final thickness of the rolled product. Of course, any adverse effects of high reductions per pass must also be considered.

6.20 List and explain the methods that can be used to reduce the roll force.

In reviewing the mechanics of a flat rolling operation, described in Section 6.3.1 starting on p. 290, it will be apparent that the roll force, F, can be reduced by:

(a) using smaller-diameter rolls,
(b) taking lower reduction per pass,
(c) reducing friction,
(d) increasing strip temperature, and
(e) applying front and/or back tensions, σ_f and σ_b.

6.21 Explain the advantages and limitations of using small-diameter rolls in flat rolling.

The advantages of using smaller diameter rolls in flat rolling are the following:

(a) compressive residual stresses are developed on the workpiece surface,
(b) lower roll forces are required,
(c) lower power requirements,
(d) less spreading, and
(e) the smaller diameter rolls are less costly and easier to replace and maintain.

The disadvantages include:

(a) larger roll deflections, possibly requiring backup rolls, and
(b) lower possible drafts; see Eq. (6.46) on p. 298.

6.22 A ring-rolling operation is being used successfully for the production of bearing races. However, when the bearing race diameter is changed, the operation results in very poor surface finish. List the possible causes, and describe the type of investigation you would conduct to identify the parameters involved and correct the problem.

Surface finish is closely related to lubricant film thickness, thus initial investigations should be performed to make sure that the film thickness is maintained the same for both bearing races. Some of the initial investigations would involve making sure, for example, that the lubricant supply is not reduced with a larger race size. Also, the higher the rolling speed, the greater the film thickness, so it should be checked that the rolling speed is the same for both cases. Forward slip should be measured and the rolling speeds adjusted accordingly.

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6.23 Describe the importance of controlling roll speed, roll gap, temperature, and other relevant process variables in a tandem-rolling operation.

Control of tandem rolling is especially important because the conditions at a particular stand can affect the those at another stand. For example, with roll gap and rolling speeds, the effect of poor control is the application of too much or too little front and/or back tension. As is clear from the description on p. 301, this may result in larger roll forces and torques, or can lead to chatter.

6.24 Is it possible to have a negative forward slip? Explain.

It is possible to have negative forward slip, but only in the presence of a large front tension. Consider that it is possible to apply a large enough front tension so that the rolls slip. A slightly lower front tension will have significant slippage, so the workpiece velocity will be much lower than the roll velocity. From Eq. (6.24) onp. 291, the forward slip will be negative. Note that it is not possible to have negative forward slip if there are no front or back tensions.

6.25 In addition to rolling, the thickness of plates and sheets can also be reduced by simply stretching. Would this process be feasible for high-volume production? Explain.

Although stretching may first appear to be a feasible process, there are several significant limitations associated with it, as compared to rolling:

(a) The stretching process is a batch operation and it cannot be continuous as in rolling.

(b) The reduction in thickness is limited by necking of the sheet, depending on its strain-hardening exponent, n.

(c) As the sheet is stretched, the surface finish becomes dull due to the orange-peel effect, and thickness and width control becomes difficult.

(d) Stretching the sheet requires some means of clamping at its ends which, in turn, will leave marks on the sheet, or even cause tearing.

(e) There would be major difficulties involved in applying high temperature during stretching of less ductile materials.

6.26 In Fig. 6.33, explain why the neutral point moves towards the roll-gap entry as friction increases.

The best way to visualize this situation is to consider two extreme conditions. Let's first assume that friction at the roll-strip interface is zero. This means that the roll is slipping with respect to the strip and as a result, the neutral (no-slip) point has to move towards the exit. On the other hand, if we assume that friction is very high, the roll tends to pull the strip with it; in this case, the neutral point will tend to move towards the entry of the roll gap.

6.27 What typically is done to make sure the product in flat rolling is not crowned?

There are a number of strategies that can be followed to make sure that the material in flat rolling is not crowned, that is, to make sure that its thickness is constant across the width. These include:

(a) Use work rolls that are crowned.

(b) Use larger backing rolls that reduce elastic deformation of the work rolls.

(c) Apply a corrective moment to the shafts of the work rolls.

(d) Use a roll material with high stiffness.

6.28 List the possible consequences of rolling at (a) too high of a speed and (b) too low of a speed.

There are advantages and disadvantages to each. Rolling at high speed is advantageous in that production rate is increased, but it has disadvantages as well, including:

- The lubricant film thickness entrained will be larger, which can reduce friction and lead to a condition where the rolls slip against the workpiece. This can lead to a damaged surface finish on the workpiece.
- The thicker lubricant film associated with higher speeds can result in significant orange-peel effect, or surface roughening.
- Because of the higher speed, chatter may occur, compromising the surface quality or process viability.

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- There is a limit to speed associated with the power source that drive the rolls.

Rolling at low speed is advantageous because the surface roughness of the strip can match that of the rolls (which can be polished). However, rolling at too low a speed has consequences such as:

- Production rate will be low, and thus the cost will be higher.
- Because a sufficiently thick lubricant film cannot be developed and maintained, there may be a danger of transferring material from the workpiece to the roll (pickup), thus compromising surface finish.
- The strip may cool excessively before contacting the rolls. This is because a long billet that is rolled slowly will lose some of its heat to the environment and also by conduction through the roller conveyor.

6.29 Rolling may be described as a continuous forging operation. Is this description appropriate? Explain.

This is a good analogy. Consider the situation of forging a block to a thinner cross section through increments (as in incremental forming). As the number of stages increases, the operation eventually approaches that of the strip profile in rolling.

6.30 Referring to appropriate equations, explain why titanium carbide is used as the work roll in Sendzimir mills, but not generally in other rolling mill configurations.

The main reason that titanium carbide is used in a Sendzimer mill is that it has a high elastic modulus, and thus will not flatten as much; see Eq. (6.48) on p. 299 and the text immediately after this equation. Titanium carbide is not used for other roll configuration because of the size of the rolls required and the high cost of TiC rolls.

Extrusion

6.31 It was stated that the extrusion ratio, die geometry, extrusion speed, and billet temperature all affect the extrusion pressure. Explain why.

Extrusion ratio is defined as the ratio of billet (initial) area to final area. If redundant work is neglected, the absolute value of true strain is $\epsilon = \ln(A_o/A_f)$. Thus, the extrusion ratio affects the extrusion force directly in an ideal situation. Die geometry has an effect because it influences material flow and, thus, contributes to the redundant work of deformation. Extrusion speed has an effect because, particularly at elevated temperatures, the flow stress will increase with increasing strain rate, depending on the strain-rate sensitivity of the workpiece material. On the other hand, higher temperatures lower the yield stress and thus, reduce forces.

6.32 How would you go about preventing centerburst defects in extrusion? Explain why your methods would be effective.

Centerburst defects are attributed to a state of hydrostatic tensile stress at the centerline of the deformation zone in the die. The two major variables affecting hydrostatic tension are the die angle and extrusion ratio. These defects can be reduced or eliminated by lowering the die angle, because this increases the contact length for the same reduction and thereby increases the deformation zone. Similarly, a higher extrusion ratio also increases the size and depth of the deformation zone, and thus will reduce or eliminate the formation of these cracks. These considerations are also relevant to strip, rod, and wire drawing.

6.33 How would you go about making a stepped extrusion that has increasingly larger cross-sections along its length? Is it possible? Would your process be economical and suitable for high production runs? Explain.

If the product has a stepped profile, such as a round stepped shaft with increasing diameter, the smaller diameter is extruded first. The die is then changed to one with a larger opening and the part is extruded further. A still larger third, and further larger cross sections, can be produced by changing the die to a larger diameter opening. The process would obviously not be economical at all for high production runs. For shorter pieces, it is possible to make a die with a stepped profile, as shown in Fig. 6.57 on p. 317, where the length of the stroke is small.

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6.34 Note from Eq. (6.54) that, for low values of the extrusion ratio, such as $R = 2$, the ideal extrusion pressure p can be lower than the yield stress, Y, of the material. Explain whether or not this phenomenon is logical.

Equation (6.54) on p. 310 is based on the energy principle and is correct. Note that the extrusion pressure, p, acts on the (undeformed) billet area. Consequently, it is not necessary that its magnitude be at least equal to the yield stress of the billet material.

6.35 In hydrostatic extrusion, complex seals are used between the ram and the container, but not between the extrusion and the die. Explain why.

The seals are not needed because the leading end of the workpiece, in effect, acts as a seal against the die. The clearance between the workpiece and the die is very small, so that the hydraulic fluid in the container cannot leak significantly. This may present some startup problems, however, before the workpiece becomes well-conformed to the die profile.

6.36 List and describe the types of defects that may occur in (a) extrusion and (b) drawing.

Recognizing that a defect is a situation that can cause a workpiece to be considered unsuitable for its intended operation, several defects can occur. Extrusion defects are discussed in Section 6.4.4 starting on p. 318. Examples include poor surface finish or surface cracking (such as bamboo defect), tailpipe or fishtailing, and chevron cracking. In drawing, defects include poor surface finish and chevron cracking. Both extrusion and drawing also can have a loss in dimensional accuracy, particularly as attributed to die wear.

6.37 What is a land in a die? What is its function? What are the advantages and disadvantages to having no land?

The land is shown in Fig. 6.60 on p. 320 for drawing, but is too small to be seen for the figures illustrating extrusion. The land is the portion of a die that is parallel to the workpiece travel that bears against the workpiece. The land is needed to ensure that workpiece dimensions are controlled and that die wear does not affect dimensions, since die wear mainly occurs on the inlet side of the die. The disadvantage to the land is that the workpiece surface can be damaged by scratching against the land; generally, the smaller the land, the better the workpiece surface.

6.38 Under what circumstances is backwards extrusion preferable to direct extrusion? When is hydrostatic extrusion preferable to direct extrusion?

Comparing Figs. 16.47a and 16.47b on p. 309 it is obvious that the main difference is that in backward extrusion the billet is stationary, and in direct extrusion it is moving relative to the container walls. The main advantage becomes clear if a glass pillow is used to provide hot-working lubricant between the workpiece and the die. On the other hand, if there is significant friction between the workpiece and the chamber, energy losses associated with friction are avoided in backwards extrusion (because there is no movement between the bodies involved).

6.39 What is the purpose of a container liner in direct extrusion (see Fig. 6.47a)? Why is there no container liner used in hydrostatic extrusion?

The container liner is used as a sacrificial wear part, similar to the pads used in an automotive disk brake. When worn, it is far less expensive to replace a liner than to replace the entire container. In hydrostatic extrusion, the billet doesn't contact the container, and thus wear is not a concern.

Drawing

6.40 We have seen that in rod and wire drawing, the maximum die pressure is at the die entry. Why?

The reason is that at the die entry, the state of stress is plane stress with equal biaxial compression (in the radial direction). Thus, according to yield criteria the state of stress is in the third quadrant of Fig. 2.36 on p. 67 and hence the pressure has a value of Y. At the die exit, however, we have longitudinal tension and biaxial (radial) compression due to contact with the die. According to the yield criteria, because

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of the tensile stress present, the die pressure is lower than that at the entry to the die (see also Answer 6.43 below).

6.41 Describe the conditions under which wet drawing and dry drawing, respectively, are desirable.

Wet drawing would be suitable for large coils of wire that can be dipped fully in the lubricant, whereas dry drawing would be suitable for straight short rods.

6.42 Name the important process variables in drawing, and explain how they affect the drawing process.

These are described in Section 6.5 starting on p. 320. The important variables include:

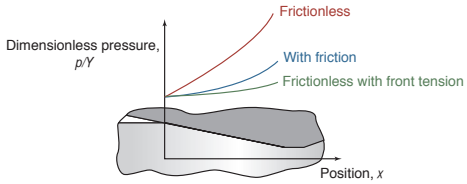
- Yield stress, Y; it directly affects the draw stress and die life.
- Die angle, α. The die angle in the deformation zone affects the redundant work; in the entry area, the die angle is important for encouraging lubricant entrainment.
- Friction coefficient, μ. The friction coefficient affects the frictional component of work and, hence, the draw stress. See also Eq. (6.68) on p. 322.
- Reduction in area. As described, there is a limit to the reduction in area that can be achieved in drawing.
- Lubrication condition. Effective lubrication reduces friction, but also may lead to a rough surface due to the orange peel effect.

6.43 Assume that a rod drawing operation can be carried out either in one pass or in two passes in tandem. If the die angles are the same and the total reduction is the same, will the drawing forces be different? Explain.

The drawing forces will be the same, unless the surface of the rod is undergoing some changes while it is between the two dies, due to external effects such as the environment or additional lubrication. The reason why the forces are not different is that the drawing process can be regarded as consisting of a series of incremental reductions taking place in one die. Ideally, we can slice the die into a number of segments and, thus, make it a tandem process. Note that as the distance between the individual die segments decreases, we approach the one-die configuration. Also note that in a tandem operation, the front tension of one segment becomes the back tension of an adjacent segment.

6.44 Refer to Fig. 6.60 and assume that reduction in the cross section is taking place by pushing a rod through the die instead of pulling it. Assuming that the material is perfectly plastic, sketch the die-pressure distribution, for the following situations: (a) frictionless, (b) with friction, and (c) frictionless but with front tension. Explain your answers.

Note that the mathematical models developed for drawing and extrusion predict the draw stress or extrusion pressure, but do not show the die pressure. A quantitative relationship could be derived for the die pressure, recognizing that $p - \sigma_x = Y'$ based on yield criteria, and then examining Eqs. (6.63) through (6.67) on p. 321. However, a qualitative sketch of the die pressure can be generated based on the physical understanding of the friction hill and associated pressure plots in forging and rolling in Sections 6.2 and 6.3. A qualitative sketch of the die pressures is given below. Note that the actual position of the curve for the frictionless case with front tension depends on the level of front tension provided.



6.45 In deriving Eq. (6.74), no mention was made regarding the ductility of the original material being drawn. Explain why.

The derivation of Eq. (6.77) on p. 326 is based on the fact that, at failure, the tensile stress in the wire or rod has reached the uniaxial yield stress of the material. Thus, it is implicitly assumed that the material is able to undergo the reduction in cross-sectional area and that it is ultimately failing under high tensile stresses.

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Note that a less ductile material will fail prematurely because of lack of ductility but not lack of strength.

6.46 Why does the die pressure in drawing decreases toward the die exit?

We refer to Eq. (6.71) on p. 322 which represents yield criteria in the deformation zone. Note that as we approach the die exit, the drawing stress, σ, increases; consequently, the die pressure, p, must decrease, as also shown in Fig. 6.62 on p. 322.

6.47 What is the magnitude of the die pressure at the die exit for a drawing operation that is being carried out at the maximum reduction per pass?

The die pressure at the exit in this case will be zero. This is because of the condition set by Eq. (6.73) on p. 324 which deals only with uniaxial stress. Note that there is a finite die pressure in a normal drawing operation, as depicted in Fig. 6.62 on p. 322, and that the drawing stress at the exit is lower than the uniaxial yield stress of the material, as it should for a successful drawing operation to take place.

6.48 Explain why the maximum reduction per pass in drawing should increase as the strain-hardening exponent, n, increases.

The reason is that the material is continuously strain hardening as it reaches the die exit. Consequently, at the exit it is stronger and, thus, can resist higher stresses before it yields. Consequently, a strain-hardening material can undergo higher reductions per pass, as can also be seen in Example 6.8.

6.49 If, in deriving Eq. (6.74), we include friction, will the maximum reduction per pass be the same (that is, 63%), higher, or lower? Explain.

If we include friction, the drawing stress will be higher. As a result, the maximum reduction per pass will be lower than 63%. In other words, the cross-sectional area of the exiting material has to be larger than the ideal case in order to support the increased drawing stress due to friction, without yielding.

6.50 Explain what effects back tension has on the die pressure in wire or rod drawing, and discuss why these effects occur.

The effect of back pressure is similar to that of back tension in rolling (see Figs. 6.35 on p. 295 and 6.62 on p. 322), namely, the pressure drops. This satisfies yield criteria, in that, as tension increases, the apparent compressive yield stress of the material decreases.

6.51 Explain why the inhomogeneity factor, ϕ, in rod and wire drawing depends on the ratio, h/L, as plotted in Fig. 6.12.

By observing Figs. 6.12 on p. 276 and 6.13b on p. 277, we note that the higher the h/L ratio, the more nonuniform the deformation of the material. For example, keeping h constant (hence the same initial and final diameters), we note that as L decreases, the die angle has to become larger. This, in turn, indicates higher redundant work (see Fig. 6.51 on p. 311).

6.52 Describe the reasons for the development of the swaging process.

The major reasons include:

(a) variety of parts that can be produced with relatively simple tooling,
(b) capacity to produce internal profiles on long workpieces,
(c) compact equipment,
(d) good surface finish and dimensional accuracy, and
(e) improved workpiece properties due to cold working of the material.

6.53 Occasionally, wire drawing of steel will take place within a sheath of a soft metal, such as copper or lead. Why would this procedure be effective?

The main reason that steel wire drawing takes place in a sheath of a softer metal is to reduce the frictional stress. Recall from Eq. (4.5) on p. 140 that, for the same friction factor, m, the frictional stress is lower if the workpiece hardness is lower. By placing the sheath in contact with the die, the soft metal acts as a solid lubricant and reduces the frictional stresses. This, in turn, reduces forces and hence increases drawability.

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6.54 Recognizing that it is very difficult to manufacture a die with a submillimeter diameter, how would you produce a 10 μm-diameter wire?

The most common method of producing very small wires is through bundle drawing, wherein a large number of wires (up to hundreds) are simultaneously drawn through one die. Special care must be taken to provide good lubrication; otherwise, the wires will weld together during drawing. The student should be encouraged to suggest additional techniques.

6.55 What changes would you expect in the strength, hardness, ductility, and anisotropy of annealed metals after they have been drawn through dies? Why?

We would expect that the yield stress of the material is higher, assuming that the operation is performed at room temperature. Since it is directly related to strength, hardness is also higher. The ductility is expected to decrease, as the material has been strain hardened. Because of preferred orientation during deformation, some anisotropy is also to be expected in cold-drawn rods.

General

6.56 With respect to the topics covered in this chapter, list and explain specifically two examples each where friction (a) is desirable and (b) is not desirable.

The student is encouraged to provide several specific examples. For example, friction is desirable in rolling and controlling material flow in forging. It is undesirable in rod and wire drawing (except to obtain a burnished surface) and extrusion.

6.57 Choose any three topics from Chapter 2 and with a specific example for each, show their relevance to the topics covered in this chapter.

By the student. For example, a student could discuss yield criteria, and then show how they are used to develop pressure and force equations for specific operations.

6.58 Same as Question 6.57 but for Chapter 3.

By the student. For example, a student could select thermal effects on mechanical properties, as discussed in Section 3.7 starting on p. 98, and apply it to a discussion of cold versus hot forging.

6.59 List and explain the reasons that there are so many different types of die materials used for the processes described in this chapter.

Among several reasons are the level of stresses and type of loading involved (such as static or dynamic), relative sliding, temperature, thermal cycling, dimensional requirements, size of workpiece, frictional considerations, wear, and economic considerations.

6.60 Why should we be interested in residual stresses developed in parts made by the forming processes described in this chapter.

Residual stresses and their significance are discussed in detail in Section 2.10 starting on p. 59. The student should elaborate further with specific references to the processes discussed in this chapter.

6.61 Make a summary of the types of defects found in the processes described in this chapter. For each type, specify methods of reducing or eliminating the defects.

By the student; see also Sections 3.8, 4.2, and 4.3.

Problems

Forging

6.62 In the free-body diagram in Fig. 6.4b, the in-

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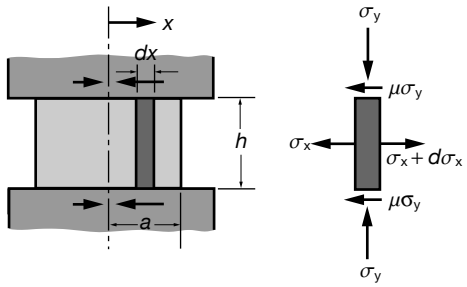
cremental stress $d\sigma_x$ on the element was shown pointing to the left. Yet it would appear that, because of the direction of frictional stresses, μp, the incremental stress should point to the right in order to balance the horizontal forces. Show that the same answer for the forging pressure is obtained regardless of the direction of this incremental stress.

We will derive the pressure using the same approach as described in Section 6.2.2 starting on p. 269. The equivalent version of Fig. 6.4 on p. 269 is shown below.



Using the stresses as shown in part (b), we have, from equilibrium and assuming unit width,

$$(\sigma_x + d\sigma_x)\, h - 2\mu\sigma_y dx - \sigma_x h = 0$$

or

$$d\sigma_x - \frac{2\mu\sigma_y}{h} dx = 0$$

For the distortion-energy criterion, it should be recognized that σ_x is now tensile, whereas in the text it is compressive. Therefore, Eq. (6.11) becomes

$$\sigma_y + \sigma_y = \frac{2}{\sqrt{3}} Y = Y'$$

Thus

$$d\sigma_x = -d\sigma_y$$

When substituted into the equilibrium equation, one obtains

$$\sigma_y = Ce^{-2\mu x/h}$$

Using the boundary conditions that $\sigma_x = 0$ (and therefore $\sigma_y = Y'$) at $x = 0$, gives the value of C as

$$C = Y' e^{2\mu a/h}$$

Therefore, substituting into the expression for σ_y,

$$\begin{aligned} \sigma_y &= Ce^{-2\mu x/h} = Y' e^{2\mu a/h} e^{-2\mu x/h} \\ &= Y' e^{2\mu(a-x)/h} \end{aligned}$$

which is the same as Eq. (6.13) on p. 270.

6.63 Plot the force vs. reduction in height curve in open-die forging of a solid cylindrical, annealed copper specimen 2 in. high and 1 in. in diameter, up to a reduction of 70%, for the cases of (a) no friction between the flat dies and the specimen, (b) $\mu = 0.25$, and (c) $\mu = 0.5$. Ignore barreling and use average-pressure formulas.

For annealed copper we have, from Table 2.3 on p. 37, $K = 315$ MPa $= 46{,}000$ psi and $n = 0.54$. The flow stress is

$$Y_f = (46{,}000 \text{ psi})\epsilon^{0.54}$$

where the absolute value of the strain is

$$\epsilon = \ln\left(\frac{h_o}{h}\right)$$

From volume constancy, we have

$$\frac{\pi}{4} r_o^2 h_o = \frac{\pi}{4} r^2 h$$

or

$$r = \sqrt{r_o^2 \left(\frac{h_o}{h}\right)}$$

Note that $r_o = 0.5$ in and $h_o = 2$ in. The forging force is given by Eqs. (6.18) and (6.19) on p. 272 as:

$$F = Y_f \left(1 + \frac{2\mu r}{3h}\right)(\pi r^2)$$

Some of the points on the curves are the following:

	Forging Force, kip		
% Red.	$\mu = 0$	$\mu = 0.25$	$\mu = 0.5$
10	11.9	12.4	13.1
20	20.1	21.3	22.4
30	29.6	31.7	33.8
40	41.9	45.6	49.4
50	59.3	66.3	73.6
60	86.1	100.	114.
70	133.1	167.	201.

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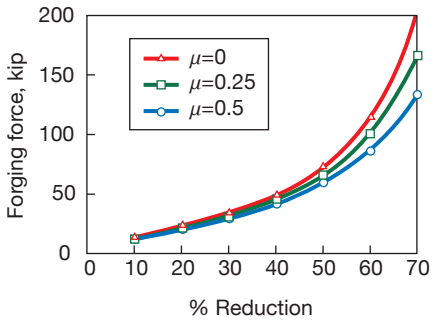
The curve is plotted as follows:



6.64 Use Fig. 6.9b to provide the answers to Problem 6.63.

The force required for forging is the product of the average pressure and the instantaneous cross-sectional area. The average pressure is obtained from Fig. 6.9b on p. 272. Note that for $\mu = 0$, $p_{\text{ave}}/Y_f = 1$, and thus the answer is the same as that to Problem 6.63 given above. The following table can be developed where p_{ave}/Y_f is obtained from Fig 6.9b, and h and r are calculated as in Problem 6.63. Note that Fig. 6.9b does not give detailed information for $2r/h < 10$, which is where the data for this problem lies. However, the $\mu = 0.25$ values (interpolated between the $\mu = 0.2$ and $\mu = 0.3$ curves) are noticeably above 1 by $2r/h = 5$ or so, so we give the value 1.25, and all intermediate values are linearly interpolated from this reading. Similarly, for $\mu = 0.5$, a value between $\mu = 0.3$ and sticking suggests p_{ave}/Y is around 1.6 or so by $2r/h = 3$. This is the basis for the numbers below.

%		p_{ave}/Y_f	
Red.	$2r/h$	$\mu = 0.25$	$\mu = 0.5$
10	0.585	1.0	1.
20	0.699	1.041	1.1
30	0.854	1.083	1.2
40	1.08	1.125	1.3
50	1.41	1.17	1.4
60	1.98	1.21	1.5
70	3.04	1.25	1.6

Recall from Problem 6.63 that

$$Y_f = (46,000 \text{ psi})\epsilon^{0.54}$$

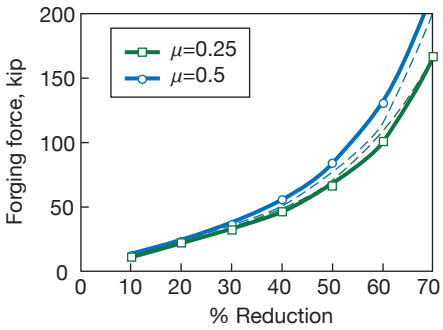
where the absolute value of the strain is

$$\epsilon = \ln\left(\frac{h_o}{h}\right)$$

From this, the following forces are calculated (recall that $F = p_{\text{ave}}A$):

%		F, kip	
Red.	r, in.	$\mu = 0.25$	$\mu = 0.5$
10	0.527	11.9	11.9
20	0.559	20.9	22.1
30	0.598	32.0	35.5
40	0.646	47.1	54.4
50	0.707	69.1	83.0
60	0.791	104.	129.
70	0.913	166.	213.

The results are plotted below. For comparison purposes, the results from Problem 6.63 are also included as dashed lines. As can be seen, the results are fairly close, even with the rough interpolation done in this solution.



6.65 Calculate the work done for each case in Problem 6.63.

The work done can best be calculated by obtaining the area under the curve F vs. Δh. From the solution to Problem 6.63, the force is given by

$$F = Y_f\left(1 + \frac{2\mu r}{3h}\right)(\pi r^2)$$

where

$$r = \sqrt{r_o^2\left(\frac{h_o}{h}\right)}$$

and

$$Y_f = (46,000 \text{ psi})\left[\ln\left(\frac{h_o}{h}\right)\right]^{0.54}$$

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Numerous mathematical software packages can perform this calculation. The results are as follows for the data in Problem 6.63, at 70% reduction in height (or $\Delta h = 1.4$):

μ	Work (in.-lb)
0	62,445
0.25	71,065
0.5	79,685

6.66 Determine the temperature rise in the specimen for each case in Problem 6.63, assuming that the process is adiabatic and the temperature is uniform throughout the specimen.

To determine the temperature rise at 70% reduction in height, we obtain the work done from Problem 6.65 above. Assuming there is negligible stored energy, this work is converted into heat. Thus, we can calculate the temperature rise using Eq. (2.65) on p. 73:

$$\Delta T = \frac{u_{\text{total}}}{\rho c}$$

where u is the specific energy, or the energy per volume. The volume of the specimen is

$$V = \pi r^2 h = \pi(0.5)^2(2) = 1.57 \text{ in}^3$$

The specific heat of copper is given in Table 3.3 on p. 106 as 385 J/kgK or 0.092 BTU/lb°F. Since 1 BTU= 780 ft-lb, the specific heat of copper is 861 in-lb/lb°F. The density of copper is, from the same table, 8970 kg/m^3 or 0.324 lb/in^3. Thus, using the work values obtained in Problem 6.65, the temperature rise is as follows:

μ	ΔT, °F
0	142
0.25	162
0.5	182

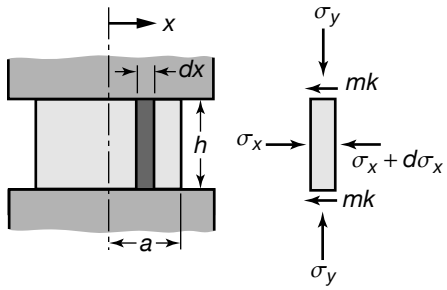
6.67 To determine its forgeability, a hot-twist test is performed on a round bar 25 mm in diameter and 200 mm long. It is found that the bar underwent 200 turns before it fractured. Calculate the shear strain at the outer surface of the bar at fracture.

The shear strain can be calculated from Eq. (2.22) on p. 49 where $r = 25/2 = 12.5$ mm, $l = 200$ mm, and $\phi = 2\pi(200) = 1257$ radians. Therefore, the shear strain is

$$\gamma = \frac{(12.5)(1257)}{200} = 78.6$$

6.68 Derive an expression for the average pressure in plane-strain compression under the condition of sticking friction.

Sticking friction refers to the condition where a Tresca friction model is used with $m = 1$ [see Eq. (4.5) on p. 140]. Therefore, the following figure represents the applied stresses to an element of forging, which can be compared to Fig. 6.4b on p. 269. The approach in Section 6.2.2 starting on p. 269 is followed closely in this derivation.



From equilibrium in the x-direction,

$$(\sigma_x + d\sigma_x)\, h + 2mkdx - \sigma_x h = 0$$

Solving for $d\sigma_x$,

$$d\sigma_x = -\frac{2mk}{h}dx$$

Integrating,

$$\sigma_x = -\frac{2mk}{h}x + C$$

where C is a constant. The boundary condition is that at $x = a$, $\sigma_x = 0$, so that

$$0 = -\frac{2mk}{h}(a) + C$$

Therefore,

$$C = \frac{2mk}{h}a$$

and

$$\sigma_x = \frac{2mk}{h}(a - x)$$

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The die pressure is obtained by applying Eq. (2.36) on p. 64:

$$\sigma_y - \sigma_x = Y'$$

Note that in plane strain, $Y' = \frac{2}{\sqrt{3}}Y$, and $k = Y/\sqrt{3}$ (see Section 2.11.3 on p. 66), so that $k = Y'/2$. Therefore

$$\sigma_y - \frac{mY'}{h}(a - x) = Y'$$

or

$$\sigma_y = Y'\left[1 + \frac{m}{h}(a - x)\right]$$

Note that this relationship is consistent with Fig. 6.10 on p. 273 for $0 \leq x \leq a$. Since the relationship is linear, then we can note that

$$\bar{\sigma_y} = \frac{Y'}{2}\left[\left(1 + \frac{ma}{h}\right) + (1)\right]$$

or

$$\bar{\sigma_y} = Y'\left(1 + \frac{ma}{2h}\right)$$

For sticking, $m = 1$ and

$$\bar{\sigma_y} = Y'\left(1 + \frac{a}{2h}\right)$$

6.69 What is the magnitude of μ when, for plane-strain compression, the forging load with sliding friction is equal to the load with sticking friction? Use average-pressure formulas.

The average pressure with sliding friction is obtained from Eq. (6.15) on p. 271, and for sticking friction it is obtained from the answer to Problem 6.68 using $m = 1$. Equating these two average pressures, we obtain

$$Y'\left(1 + \frac{\mu a}{h}\right) = Y'\left(1 + \frac{a}{2h}\right)$$

Therefore, $\mu = 0.5$.

6.70 Note that in cylindrical upsetting, the frictional stress cannot be greater than the shear yield stress, k, of the material. Thus, there may be a distance x in Fig. 6.8 where a transition occurs from sliding to sticking friction. Derive an expression for x in terms of r, h, and μ only.

The pressure curve for the solid cylindrical case is similar to Fig. 6.5 on p. 270 and is given by Eq. (6.17) on p. 272. Following the same procedure as in Example 6.2, the shear stress at the interface due to friction can be expressed as

$$\tau = \mu p$$

However, we know that the shear stress cannot exceed the yield shear stress, k, of the material which, for the cylindrical state of stress, is $\frac{Y}{2}$. Thus, in the limit, we have the condition

$$\mu Y e^{2\mu(r-x)/h} = \frac{Y}{2}$$

or

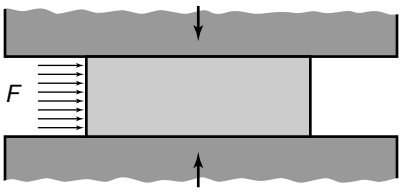
$$\frac{2\mu(r - x)}{h} = \ln\left(\frac{1}{2\mu}\right)$$

Hence,

$$x = r - \left(\frac{h}{2\mu}\right)\ln\left(\frac{1}{2\mu}\right)$$

Note that this answer is the same as in the example problem for plane strain.

6.71 Assume that the workpiece shown in the accompanying figure is being pushed to the right by a lateral force F while being compressed between flat dies. (a) Make a sketch of the die-pressure distribution for the condition for which F is not large enough to slide the workpiece to the right. (b) Make a similar sketch, except that F is now large enough so that the workpiece slides to the right while being compressed.



Applying a compressive force to the left boundary of the workpiece in Fig. 6.5 on p. 270 raises the pressure at that boundary. The higher the force F, the higher the pressure. Eventually the workpiece will slide completely to the right, indicating that the neutral point has now moved all the way to the left boundary. These are depicted in the figure below.

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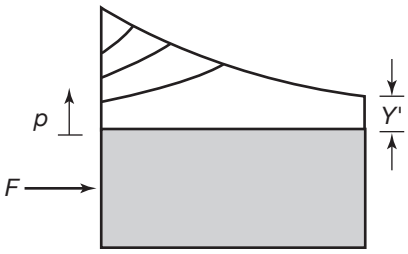

6.72 For the sticking example given in Fig. 6.10, derive an expression for the lateral force F required to slide the workpiece to the right while the workpiece is being compressed between flat dies.

Because we have sticking on both die-workpiece interfaces and a plane-strain case, the frictional stress will simply be $Y'/2$. Hence, the lateral force required must overcome this resistance on both (top and bottom) surfaces. Thus,

$$F = 2Y'(2a)(w) = 4Y'aw$$

where w is the width of the workpiece, i.e., the dimension perpendicular to the page in the figure.

6.73 Two solid cylindrical specimens, A and B, both made of a perfectly-plastic material, are being forged with friction and isothermally at room temperature to a reduction in height of 25%. Originally, specimen A has a height of 2 in. and a cross-sectional area of 1 in^2, and specimen B has a height of is 1 in. and a cross-sectional area of 2 in^2. Will the work done be the same for the two specimens? Explain.

We can readily see that specimen B will require higher work because it has a larger die-workpiece surface area, hence a higher frictional resistance as compared to specimen A. We can prove this analytically by the following approach. The work done is the integral of the force and distance:

$$W = \int F\, dh$$

where $F = (p_{\text{ave}})(A)$, and p_{ave} for a cylindrical body is given by Eq. (6.18) on p. 272. Because the volume V of the workpiece is constant, we have a relationship between its radius and height as

$$r = \sqrt{\frac{V}{\pi h}}$$

Hence,

$$p_{\text{ave}} = Y\left[1 + \left(\frac{2\mu}{3}\right)\left(\frac{V}{\pi}\right)\left(\frac{1}{h^{3/2}}\right)\right]$$

Because it consists of constants, let $c = (2\mu/3)(V/\pi)$, which results in the following expression:

$$F = Y\left(1 + \frac{c}{h^{3/2}}\right)\left(\frac{V}{h}\right)$$

and hence work is

$$\begin{aligned} W &= YV\int_{h_o}^{h_o/2}\left[\left(\frac{1}{h}\right) + \left(\frac{c}{h^{5/2}}\right)\right] dh \\ &= YV\left[\ln 0.75 - \frac{3c}{2}\frac{1}{h_o^{3/2}}(0.540)\right] \\ &= YV\left[-0.288 - \frac{c}{h_o^{3/2}}(0.809)\right] \end{aligned}$$

Thus, for this problem, we have

$$\begin{aligned} W_A &= YV\left[-0.288 - c\left(\frac{1}{2^{3/2}}\right)(0.809)\right] \\ &= YV(-0.288 - 0.286c) \end{aligned}$$

$$\begin{aligned} W_B &= YV\left[-0.288 - c\left(\frac{1}{1^{3/2}}\right)(0.809)\right] \\ &= YV(-0.288 - 0.809c) \end{aligned}$$

Comparing the two shows that $W_B > W_A$.

6.74 In Fig. 6.6, does the pressure distribution along the four edges of the workpiece depend on the particular yield criterion used? Explain.

The answer is yes. This is a plane-stress problem, but an element at the center of the edges is subjected not only to a pressure p (due to the dies) but also frictional constraint since the body is expanding in all directions. Thus, an element at the center of the edges is subjected to biaxial compressive stresses. Because the lateral stress, σ_x, due to frictional forces is smaller than the normal stress (pressure), we note the following:

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(a) According to the maximum-shear-stress criterion, the pressure distribution along the edges should be constant because the minimum stress is zero. Hence,

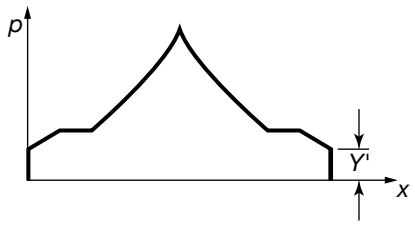
$$p = Y$$

(b) According to the distortion-energy criterion for plane stress, the pressure distribution along the edges should be as given in Fig. 6.6 on p. 271 and can be shown to obey the following relationship:

$$p^2 + \sigma^2 - p\sigma = Y^2$$

Note that at the corners $p = Y$, and that p is highest at the center along the edges because that is where the frictional stress is a maximum.

6.75 Under what conditions would you have a normal pressure distribution in forging a solid cylindrical workpiece as shown in the accompanying figure? Explain.



The pressure distribution is similar to the friction hill shown in Fig. 6.5 on p. 270, with the exception that there are two symmetric regions where the pressure is constant. These regions sustain pressure but do not contribute to the frictional stress. A trapped layer of incompressible lubricant in grooves machined on the surface of the workpiece, for example, would represent such a condition. The grooves would be filled with the lubricant, which sustains pressure but would not contribute to shear at the interface because of its low viscosity.

6.76 Derive the average die-pressure formula given by Eq. (6.15). (*Hint:* Obtain the volume under the friction hill over the surface by integration, and divide it by the cross-sectional area of the workpiece.)

The area, A, under the pressure curve (from the centerline to the right boundary a) in Fig. 6.5 on p. 270 is given by

$$A = \int p\, dx$$

and the average pressure is

$$p_{\text{ave}} = \frac{1}{a} \int p\, dx$$

where

$$p = Y' e^{2\mu(a-x)/h}$$

Integrating this equation between the limits $x = 0$ and $x = a$, we obtain

$$p_{\text{ave}} = \frac{Y'}{2\mu a/h} \left(e^{2\mu a/h} - 1 \right)$$

Letting $2\mu a/h = m$, and using a Taylor series expansion of the exponent term,

$$e^m = 1 + m + \frac{m^2}{2!} + \frac{m^3}{3!} + \ldots$$

Ignoring third-order terms and higher as being too small compared to other terms, we obtain

$$\begin{aligned} p_{\text{ave}} &= \frac{Y'}{m} \left(1 + m + \frac{m^2}{2} - 1 \right) \\ &= Y' \left(1 + \frac{m}{2} \right) \\ &= Y' \left(1 + \frac{\mu a}{h} \right) \end{aligned}$$

6.77 Take two solid cylindrical specimens of equal diameter but different heights, and compress them (frictionless) to the same percent reduction in height. Show that the final diameters will be the same.

Let's identify the shorter cylindrical specimen with the subscript s and the taller as t, and their original diameter as D. Subscripts f and o indicate final and original, respectively. Because both specimens undergo the same percent reduction in height, we can write

$$\frac{h_{tf}}{h_{to}} = \frac{h_{sf}}{h_{so}}$$

and from volume constancy,

$$\frac{h_{tf}}{h_{to}} = \left(\frac{D_{to}}{D_{tf}} \right)^2$$

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and

$$\frac{h_{sf}}{h_{so}} = \left(\frac{D_{so}}{D_{sf}}\right)^2$$

Because $D_{to} = D_{so}$, we note from these relationships that $D_{tf} = D_{sf}$.

6.78 A rectangular workpiece has the following original dimensions: $2a = 100$ mm, $h = 30$ mm and width $= 20$ mm (see Fig. 6.5). The metal has a strength coefficient of 300 MPa and a strain-hardening exponent of 0.3. It is being forged in plane strain with $\mu = 0.2$. Calculate the force required at a reduction of 20%. Do not use average-pressure formulas.

In this plane-strain problem note that the width dimension remains at 20 mm. Thus, when the reduction in height is 20%, the final height of the workpiece is

$$h = (1 - 0.2)(30) = 24 \text{ mm} = 0.024 \text{ m}$$

Since volume constancy has to be maintained and we have a plane-strain situation, we can find the new (final) dimension a from

$$(100)(30)(20) = (2a)(24)(20)$$

Thus, $a = 62.5$ mm $= 0.0625$ m. The absolute value of the true strain is

$$\epsilon = \ln\left(\frac{30}{24}\right) = 0.223$$

and hence the uniaxial flow stress at the final height is

$$Y_f = K\epsilon^n = (400)(0.223)^{0.3} = 255 \text{ MPa}$$

and the flow stress in plane strain is $Y'_f = (1.15)(255) = 293$ MPa. Thus, from Eq. (6.13) on p. 270 the pressure as a function of distance x is

$$\begin{aligned} p &= Y' e^{2\mu(a-x)/h} \\ &= (293 \text{ MPa}) e^{2(0.2)(0.0625-x)/0.024} \\ &= (293 \text{ MPa}) e^{1.042 - 16.7x} \end{aligned}$$

To obtain the force required for one-half of the workpiece per unit width, we integrate the above expression between the limits $x = 0$ and $x = 0.0625$, which gives the force per unit width and one-half of the length as $F = 32.2$ MN/m. The total force is the product of this force and the specimen width times two, or

$$F_{\text{total}} = 2(32.2)(0.02) = 1.288 \text{ MN}$$

Note that if we use the average pressure formula given by Eq. (6.16) on p. 271, the answer will be

$$\begin{aligned} F_{\text{total}} &= Y' \left(1 + \frac{\mu a}{h}\right)(2a)(w) \\ &= (293)\left[1 + \frac{(0.2)(0.0625)}{0.024}\right] \\ &\quad \times (2)(0.0625)(0.02) \\ &= 1.11 \text{ MN} \end{aligned}$$

The discrepancy is due to the fact that in deriving the average pressure, a low value of $\mu a/h$ have been assumed for mathematical simplicity.

6.79 Assume that in upsetting a solid cylindrical specimen between two flat dies with friction, the dies are rotated at opposite directions to each other. How, if at all, will the forging force change from that for nonrotating dies? (*Hint:* Note that each die will now require a torque but in opposite directions.)

From the top view of the round specimen in Fig. 6.8b on p. 272, we first note that the frictional stresses at the die-specimen interfaces will essentially be tangential. (We say essentially because the rotational speed is assumed to be much higher than the vertical speed of the dies.) Consequently, the direction of $\mu\sigma_z$ will be tangential and, because there will now be no frictional stress in the radial direction, balancing forces in the radial direction will not include friction. Thus, the situation will be basically similar to upsetting without friction, and the forging force will be a minimum. However, additional work has to be done in supplying torque to the two dies that are rotating in opposite directions. Note also that we are assuming μ to be small, so that it will not cause plastic twisting of the specimen due to die rotation.

6.80 A solid cylindrical specimen, made of a perfectly plastic material, is being upset between flat dies with no friction. The process is being carried out by a falling weight, as in a drop hammer. The downward velocity of the hammer is at a maximum when it first contacts the workpiece and becomes zero when the

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hammer stops at a certain height of the specimen. Establish quantitative relationships between workpiece height and velocity, and make a qualitative sketch of the velocity profile of the hammer. (*Hint:* The loss in the kinetic energy of the hammer is the plastic work of deformation; thus, there is a direct relationship between workpiece height and velocity.)

For this problem we will use the energy method, in which case the kinetic energy of the falling weight is being dissipated by the work of plastic deformation of the specimen. We know that the work, W, done on the specimen of volume V is

$$W = uV$$

or in terms of specific heights,

$$W = Y \ln\left(\frac{h_o}{h}\right)(V)$$

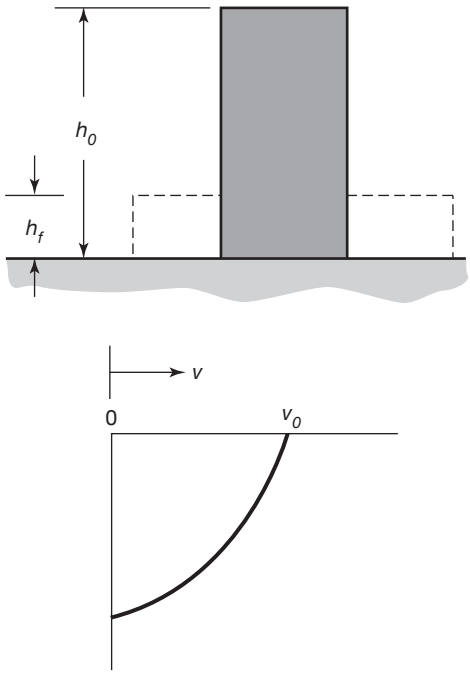
where h is the instantaneous height of the specimen. The kinetic energy, KE, of the falling weight can be expressed in terms of the initial and instantaneous heights of the specimen:

$$\text{KE} = \frac{m\left(v_o^2 - v^2\right)}{2}$$

where m is the mass of the falling body and v_o is the velocity when the falling weight first contacts the specimen. Equating the two energies, noting that Y, h_o, V, m, and v_o are constant, and simplifying, we find the relationship between v and h as

$$v \propto \sqrt{\ln h + C}$$

where C is a constant. Inspection of this equation indicates that, qualitatively, the velocity profile of the falling weight will be as shown in the following figure:



This behavior is to be expected because the specimen cross-sectional area will be increasing rapidly with time, hence the upward resisting force on the falling weight will also increase rapidly and, thus, decelerate the weight rapidly.

6.81 Describe how would you go about estimating the force acting on each die in a swaging operation.

First, an estimate has to be made of the contact area between the die and the workpiece; this can be done by studying the contact geometry. Then, a flow stress, Y_f, has to be determined, which will depend on the workpiece material, strain hardening exponent, n, and the amount of strain the material is undergoing. Also, as a first approximation, the hardness of the workpiece material can be used (with appropriate units) since the deformation zone during swaging is quite contrained, as in a hardness test. Note also that the swaging process can be assumed to be similar to hubbing, and consequently, Eq. (6.23) on p. 281 may be used to estimate the die force.

6.82 A mechanical press is powered by a 30-hp motor and operates at 40 strokes per minute. It uses a flywheel, so that the rotational speed of

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the crankshaft does not vary appreciably during the stroke. If the stroke length is 6 in., what is the maximum contact force that can be exerted over the entire stroke length? To what height can a 5052-O aluminum cylinder with a diameter of 0.5 in. and a height of 2 in. be forged before the press stalls?

Note that the power is 30 hp = 198,000 in-lb/s. Assume that the press stroke has a constant velocity. Although this is a poor approximation, it does not affect the problem since a constant force is assumed later; actually, both the force and velocity will vary. At 40 strokes per minute and with a 6 in. stroke, we would require a velocity of

$$V = (40 \text{ rpm})(12 \text{ in./rev})(60 \text{ min/s}) = 8 \text{ in./s}$$

The power exerted is the product of the force and the velocity; thus,

$$198,000 \text{ in.-lb/s} = FV = F(8 \text{ in./s})$$

or $F = 24.75$ kip. For 5052-O, the yield strength is 90 MPa=13 ksi (from Table 3.7 on p. 116). Therefore, using Eqs. (6.18) and (6.19) on p. 272,

$$\begin{aligned} F &= 24,750 \text{ lb} \\ &= Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right) \\ &= (13 \text{ ksi})\pi(r^2)\left(1 + \frac{2(0.2)r}{3h}\right) \end{aligned}$$

Also, from volume constancy we have $r^2 h = r_o^2 h_o$. Substituting this into the above equation and solving, yields $r = 0.675$ in., or a diameter of around 1.35 in. The height in this case is then $h = 0.274$ in.

6.83 Estimate the force required to upset a 0.125-in-diameter C74500 brass rivet in order to form a 0.25-in-diameter head. Assume that the coefficient of friction between the brass and the tool-steel die is 0.2 and that the rivet head is 0.125 in. in thickness.

Since we are asked for the force required to perform the forging operation, we use Eq. (6.18) on p. 272 to obtain the average pressure as evaluated at the end of the stroke where $r = 0.125$ in and $h = 0.125$ in. From Table 3.11 on p. 119 and recognizing that the bronze is annealed, so that its strength should be on the low end of the ranges given, the yield stress of C74500 bronze can be taken as $Y = 170$ MPa = 24.6 ksi. From Eq. (6.18) on p. 272, the pressure at the end of the press stroke is

$$\begin{aligned} p_{\text{ave}} &= Y\left(1 + \frac{2\mu r}{3h}\right) \\ &= (24.6)\left(1 + \frac{2(0.20)(0.125)}{3(0.125)}\right) \\ &= 27.88 \text{ ksi} \end{aligned}$$

The force is the product of pressure and area, given in Eq. (6.19) as

$$\begin{aligned} F &= p_{\text{ave}}\left(\pi r^2\right) \\ &= (27.88)\pi\left(\frac{0.125}{2}\right)^2 \end{aligned}$$

or $F = 0.342$ kip = 342 lb.

6.84 Using the slab method of analysis, derive Eq. (6.17).

We use an element and the stresses acting on it as shown in Fig. 6.8. Balancing forces in the radial direction,

$$\begin{aligned} 0 &= \sigma_r x h d\theta + 2\sigma_\theta h dx \frac{d\theta}{2} - 2\mu\sigma_z x d\theta dx \\ &\quad -(\sigma_r + d\sigma_r)(x + dx)d\theta h \end{aligned}$$

Simplifying this equation, noting that the product $dr\, d\theta$ is very small and hence can be neglected, and dividing by $xh\, dx$, we obtain

$$\frac{d\sigma_r}{dx} + \frac{\sigma_r - \sigma_\theta}{x} = -\frac{2\mu\sigma_z}{h}$$

Note that the circumferential and radial incremental strains are equal to each other by virtue of the fact that

$$d\epsilon_\theta = \frac{2\pi\, dx}{2\pi x} = \frac{dx}{d} \text{ and } d\epsilon_r = \frac{dx}{x}$$

From Eq. (2.43), we can state that

$$\frac{d\epsilon_r}{\sigma_r} = \frac{d\epsilon_\theta}{\sigma_\theta} = \frac{d\epsilon_z}{\sigma_z}$$

Consequently, we have

$$\sigma_r = \sigma_\theta$$

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and thus

$$\frac{d\sigma_r}{dx} = -\frac{2\mu\sigma_z}{h}$$

Also, using the distortion-energy criterion,

$$(\sigma_r - \sigma_\theta)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_\theta)^2 = 2Y^2$$

we have

$$\sigma_r\sigma_z = Y$$

and since the yield stress, Y, is a constant, we note that

$$d\sigma_r = d\sigma_z$$

Thus,

$$\frac{d\sigma_z}{dx} = -\frac{2\mu\sigma_z}{h}$$

Note that this equation is similar to Eq. (6.12) for plane-strain forging. Following the same procedure as in the text, we can then obtain the pressure p at any radius x as

$$p = Ye^{2\mu(r-x)/h}$$

Rolling

6.85 In Example 6.4, calculate the velocity of the strip leaving the rolls.

Because mass continuity has to be maintained, we can write

$$V_f(0.80) = V_r h_{\text{neutral}}$$

where h_{neutral} is the thickness of the strip at the neutral point and

$$V_f = \omega R = (2\pi)(100)(12) = 7540 \text{ in./min}$$

The thickness at the neutral point can be calculated from Eqs. (6.32) and (6.33) on p. 294. In this problem, we can approximate a certain thickness, based on observations regarding Figs. 6.33 on p. 293 and 6.34 on p. 294. Since the original and final thicknesses are 1.0 and 0.8 in., respectively, let's assume that $h_{\text{neutral}} = 0.85$. Thus

$$V_f = \frac{(7540)(0.85)}{0.80} = 8010 \text{ in./min}$$

or $V_f = 668$ ft/min.

6.86 With appropriate sketches, explain the changes that occur in the roll-pressure distribution if one of the rolls is idling, i.e., power is shut off to that roll.

Note in this case that the idling roll cannot supply power to the strip; hence, there cannot be a net torque acting on it (assuming no bearing friction). Consequently, the roll-pressure distribution will be such that the frictional forces acting along the entry and exit zones, respectively, are equal. In the absence of strain hardening, the pressure distribution in the roll gap will thus be symmetrical and the neutral axis shifts a little towards the entry. However, the other roll is still supplying power and its neutral axis is more towards the exit. There is, therefore, a zone in the roll gap on which the frictional stresses on the top and bottom surfaces are opposite in sign; this condition is known as *cross shear*.

6.87 It can be shown that it is possible to determine μ in flat rolling without measuring torque or forces. By inspecting the equations for rolling, describe an experimental procedure to do so. Note that you are allowed to measure any quantity other than torque or forces.

In this problem, we first measure the following quantities: v_o, v_f, v_r, h_o and h_f. From the available information and knowing R, we can calculate the magnitude of the angle of acceptance, α. From the velocity distribution, as in Fig. (6.32), we can now determine ϕ_n from which we obtain H_n, using Eq. (6.32) on p. 294. To determine the coefficient of friction, we can rewrite Eq. (6.32) as

$$\mu = \frac{\ln\left(\frac{h_o}{h_f}\right)}{H_o - 2H_n}$$

in which H_o is obtained from Eq. (6.29) on p. 292 where ϕ is now the angle α.

6.88 Derive a relationship between back tension, σ_b, and front tension, σ_f, in rolling such that when both tensions are increased, the neutral point remains in the same position.

We note that at the neutral point, the roll pressure, p, obtained from Eqs. (6.34) and (6.35) on

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p. 294 must be equal. Therefore, we can write

$$\left[Y'_f - \sigma_b\right] \frac{h_n}{h_o} e^{\mu(H_o - H_n)} = \left[Y'_f - \sigma_f\right] \frac{h_h}{h_f} e^{\mu H_n}$$

thus

$$\sigma_b = Y'_f - \frac{h_o}{h_f} \left(e^{2\mu H_n - \mu H_o}\right) \left(Y'_f - \sigma_f\right)$$

It should be noted that this equation can be rearranged into different forms.

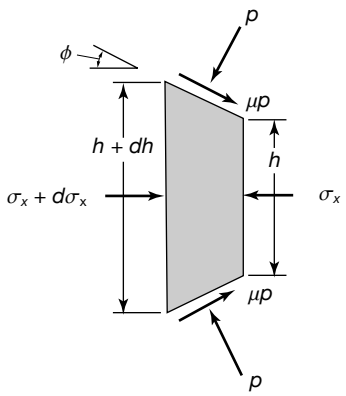
6.89 Take an element at the center of the deformation zone in flat rolling. Assuming that all the stresses acting on this element are principal stresses, indicate the stresses qualitatively, and state whether they are tensile or compressive. Explain your reasoning. Is it possible for all three principal stresses to be equal to each other in magnitude? Explain.

All stresses on the element will be compressive for the following reasons:

(a) The vertical stress (pressure) is the compressive stress applied by the rolls.

(b) The longitudinal stress is compressive because of the frictional forces in the roll gap. This can be shown by the free-body diagram given below, and the stress is always compressive throughout the gap length (in the absence of front or back tensions).

(c) The stress perpendicular to the page is also compressive because we have a plane-strain state of stress. The material is not free to expand laterally because it is constrained both by frictional forces (along the length of the rolls) as well as the rigid regions of the strip ahead and behind the roll gap.



6.90 It was stated that in flat rolling a strip, the roll force is reduced about twice as effectively by back tension as it is by front tension. Explain the reason for this difference, using appropriate sketches. (*Hint:* Note the shift in the position of the neutral point when tensions are applied.)

Referring to Figs. 6.33 on p. 293 or 6.34 on p. 294, we note that the neutral point is towards the exit, hence the area under the entry-side curve is larger than that for the exit-side curve. (This is in order to supply energy through a net frictional force during ordinary rolling.) Consequently, a reduction in the height of the curve by back tension (σ_b) has a greater effect than that for the exit side by front tension.

6.91 It can be seen that in rolling a strip, the rolls will begin to slip if the back tension, σ_b, is too high. Derive an analytical expression for the magnitude of the back tension in order to make the powered rolls begin to slip. Use the same terminology as applied in the text.

Slipping of the rolls means that the neutral point has moved to the exit of the roll gap. Thus, the whole contact area becomes the entry zone and Eq. (6.34) on p. 294 is applicable. We know that when $\phi = 0$, $H = 0$, and thus the pressure at the exit is

$$p_{\phi=0} = \left(Y'_f - \sigma_b\right) \left(\frac{h_f}{h_o}\right) e^{\mu H_o}$$

We also know that at the exit the pressure is equal to Y'. Therefore, we obtain

$$Y'_f = \left(Y'_f - \sigma_b\right) \left(\frac{h_f}{h_o}\right) e^{\mu H_o}$$

Solving for σ_b,

$$\sigma_b = Y'_f \left[1 - \left(\frac{h_o}{h_f}\right) \left(e^{-\mu H_o}\right)\right]$$

where H_o is obtained from Eq. (6.29) with $\phi = \alpha$.

6.92 Derive Eq. (6.46).

Refer to the figure below.

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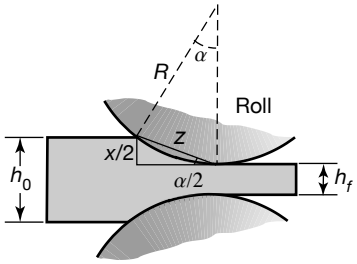

Note that $x = h_o - h_f$, and is also called the draft. For small α, $z = R \sin \alpha$. Also, note that for small angles,

$$\frac{x}{2} = \frac{z \sin \alpha}{2}$$

Therefore,

$$x = z \sin \alpha = R \tan^2 \alpha$$

At small angles, the sine and tangent functions are approximately equal; hence,

$$x = h_o - h_f = R \tan^2 \alpha$$

Recall that the inclined-plane principle for friction states that $\alpha = tan^{-1}\mu$, or $\mu = \tan \alpha$. Substituting, we have

$$h_o - h_f = R\mu^2$$

which is the desired relationship.

6.93 In Steckel rolling, the rolls are idling, and thus there is no net torque, assuming frictionless bearings. Where, then, is the energy coming from to supply the necessary work of deformation in rolling? Explain with appropriate sketches, and state the conditions that have to be satisfied.

The energy for work of deformation is supplied by the tension required to pull the strip through the roll gap. Since the rolls are idling, the roll-pressure distribution will be such that the frictional forces in the entry and exit zones, respectively, are equal. The neutral point will shift toward the entry zone, as if applying a front tension in Fig. 6.35.

6.94 Derive an expression for the tension required in Steckel rolling of a flat sheet, without friction, for a workpiece with a true-stress-true-strain curve given by $\sigma = a + b\epsilon$.

In this process, the work done in rolling is supplied by the front tension. Assuming a certain reduction in thickness per pass, we first determine the absolute value of the true strain,

$$\epsilon_1 = \ln \left(\frac{h_o}{h_f} \right)$$

Since we know the behavior of the material as $\sigma = a + b\epsilon$, we can determine the energy of plastic deformation per unit volume, u, using Eq. (2.59) on p. 71. We also know the cross-sectional dimensions of the strip and the velocities v_o and v_f. The power dissipated is the product of u and the volume rate of flow through the roll gap, which is given by the quantity $w_o h_o v_o$. This product is equal to the power supplied by the front tension that acts on the exiting cross-sectional area of the rolled strip. Hence, assuming a plane-strain condition (that is, w = constant), we can write the expression

$$uwh_o v_o = \sigma_f w h_f v_f$$

from which the magnitude of the front tension can be determined.

6.95 (a) Make a neat sketch of the roll-pressure distribution in flat rolling with powered rolls. (b) Assume now that the power to both rolls is shut off and that rolling is taking place by front tension only, i.e., Steckel rolling. Superimpose on your diagram the new roll-pressure distribution, explaining your reasoning clearly. (c) After completing part (b), further assume that the roll bearings are becoming rusty and deprived of lubrication although rolling is still taking place by front tension only. Superimpose a third roll-pressure distribution diagram for this condition, explaining your reasoning.

The relevant pressure diagram for Steckel rolling can be obtained simply from Fig. 6.35 on p. 295. Note that, with frictionless bearings, the front tension supplies the work of deformation; thus, σ_f must be high enough such that the entry and exit zones have equal areas under the pressure curve and the neutral point shifts to the left. In the case of roll bearings with friction, the front tension must increase in order to supply the additional work required to rotate the idling rolls with bearing friction. Thus, the neutral point will shift further to the left. We

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can also assume that the bearing friction is so high that they freeze. In that case, the rolls will not rotate, which means that the neutral point must shift all the way to the entry and thus frictional forces are all in one direction.

6.96 Derive Eq. (6.28), based on the equation preceding it. Comment on how different the h values are as the angle ϕ increases.

Note that the procedure is identical to the answer to Problem 6.92 above. For small drafts, and hence small angles ϕ (which is typically the case in rolling practice), the expression $\mu = \tan\alpha$ can be replaced by $\mu = \alpha$, or for the more general case, $\mu = \phi$. Consequently, the expression

$$h_o - h_f = R\mu^2$$

becomes

$$h - h_f = R\phi^2$$

so that

$$h = h_f + R\phi^2$$

which is Eq. (6.28) on p. 292.

6.97 In Fig. 6.34, assume that $L = 2L_2$. Is the roll force, F, for L now twice or more than twice the roll force for L_2? Explain.

An inspection of Fig. 6.34 on p. 294 clearly indicates that the roll force, F, will be more than twice as high. This is due to the fact that the roll-pressure distribution has the shape of a friction hill. Only when the pressure is constant through the roll gap (as in "frictionless" rolling), will the force be twice as high.

6.98 A flat-rolling operation is being carried out where $h_0 = 0.2$ in., $h_f = 0.15$ in., $w_0 = 10$ in., $R = 8$ in., $\mu = 0.25$, and the average flow stress of the material is 40,000 psi. Estimate the roll force and the torque. Include the effects of roll flattening.

The roll force can be estimated from Eq. (6.40) on p. 296, where the quantity L is obtained from Eq. (6.38). Therefore,

$$L = \sqrt{R\Delta h} = \sqrt{(8)(0.20 - 0.15)} = 0.632 \text{ in.}$$

and

$$h_{\text{ave}} = \frac{0.20 + 0.15}{2} = 0.175 \text{ in.}$$

Therefore,

$$\begin{aligned} F &= Lw\bar{Y}' \left[1 + \frac{\mu L}{2h_{\text{ave}}}\right] \\ &= (0.632)(10)(40,000)\left[1 + \frac{(0.25)(0.632)}{2(0.175)}\right] \\ &= 367,000 \text{ lb} \end{aligned}$$

We check for roll flattening by using Eq. (6.48) on p. 299, where $C = 1.6 \times 10^{-7}$ in^2/lb, assuming steel rolls, and

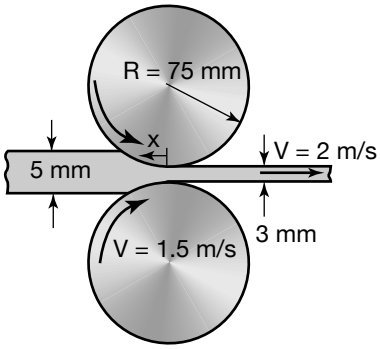
$$F' = \frac{F}{w} = \frac{367,000}{10} = 36,700 \text{ lb/in.}$$

Thus,

$$\begin{aligned} R' &= R\left(1 + \frac{CF'}{h_o - h_f}\right) \\ &= (8)\left[1 + \frac{(1.6 \times 10^{-7})(36,700)}{0.20 - 0.15}\right] \\ &= 8.94 \text{ in.} \end{aligned}$$

Using this value in the force expression, we have $L = 0.668$ in. and $F = 395,000$ lb. This force predicts a flattened radius of $R' = 9.0$ in. (Note that the expression is converging.) This radius predicts $L = 0.671$ and $F = 397,000$ lb, which suggests a radius of $R' = 9.02$ in. Therefore, the roll force is around 397,000 lb, with an effective roll radius of 9.0 in.

6.99 A rolling operation takes place under the conditions shown in the accompanying figure. What is the position x_n of the neutral point? Note that there are a front and back tension that have not been specified. Additional data are as follows: Material is 5052-O aluminum; hardened steel rolls; surface roughness of the rolls = 0.02 μm; rolling temperature = 210°C.



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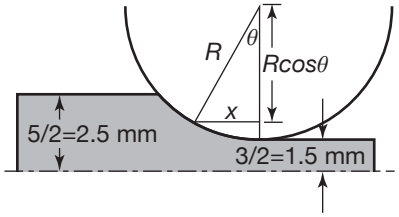
Note that more data is given than is needed to solve this problem. Assuming the material is incompressible, the velocity at the inlet is calculated as:

$$(2.0)(3 \text{ mm})w = V_i(5 \text{ mm})w$$

Therefore, $V_i = 1.20$ m/s. At the neutral point, the velocity is the roll velocity (or 1.5 m/s). Assuming incompressibility, we can compare the outlet and the neutral point:

$$(1.5)(h) = (2.0)(3) \quad \rightarrow \quad h = 4.0 \text{ mm}$$

Consider the sketch of the roll bite geometry given below.



θ can be calculated from:

$$75 - (75)\cos\theta = \frac{4-3}{2}$$

or $\theta = 6.62°$. Therefore,

$$x_n = R\sin\theta = (75)\sin 6.62° = 8.64 \text{ mm}$$

6.100 Estimate the roll force and power for annealed low-carbon steel strip 200 mm wide and 10 mm thick, rolled to a thickness of 6 mm. The roll radius is 200 mm, and the roll rotates at 200 rpm. Let $\mu = 0.1$.

The roll force can be estimated from Eq. (6.40) on p. 296, where the quantity L is obtained from Eq. (6.38). Therefore,

$$L = \sqrt{R\Delta h} = \sqrt{(200)(4)} = 28.3 \text{ mm}$$

and

$$h_{\text{ave}} = \frac{10+6}{2} = 8 \text{ mm}$$

From Table 2.3 on p. 37, $K = 530$ MPa and $n = 0.26$. The strain is

$$\epsilon = \ln\frac{10}{6} = 0.5108$$

The average yield stress can be obtained from Eq. (2.60) on p. 71 as

$$\bar{Y} = \frac{K\epsilon^{n+1}}{n+1} = \frac{(530)(0.5108)^{1.26}}{1.26} = 180 \text{ MPa}$$

and

$$\bar{Y}' = (1.15)\bar{Y} = 207 \text{ MPa}$$

Therefore,

$$\begin{aligned} F &= Lw\bar{Y}'\left(1 + \frac{\mu L}{2h_{\text{ave}}}\right) \\ &= (0.0283)(0.2)(207)\left[1 + \frac{(0.1)(28.3)}{2(8)}\right] \\ &= 1.38 \text{ MN} \end{aligned}$$

The power per roll is given by Eq. (6.43) as

$$P = \frac{\pi FLN}{60,000} = \frac{\pi(1.38 \times 10^6)(0.0283)(200)}{60,000}$$

or $P = 409$ kW.

6.101 Calculate the individual drafts in each of the stands in the tandem-rolling operation shown.

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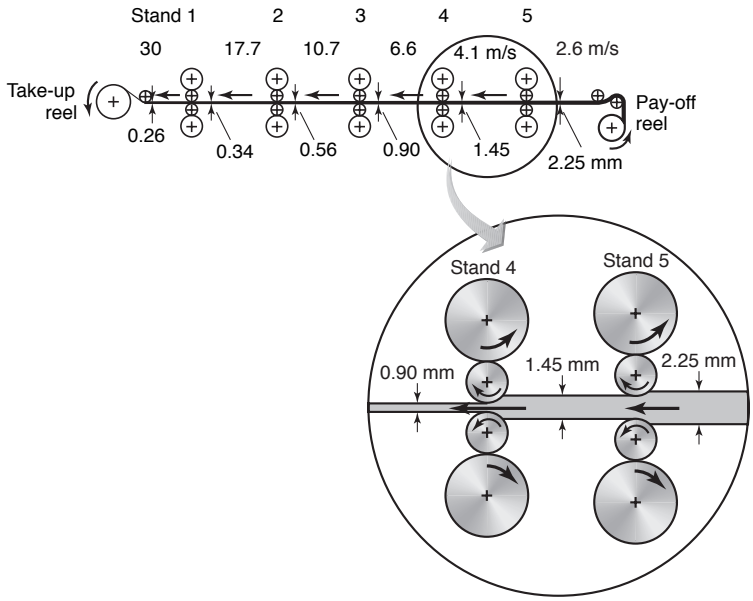

In Section 6.3.1 starting on p. 290, the draft was defined as Δh for a rolling operation. Therefore, the answers are:

- Stand 5: 2.25 - 1.45 = 0.80 mm, or 36%.
- Stand 4: 1.45 - 0.90 = 0.55 mm, or 38%.
- Stand 3: 0.90 - 0.56 = 0.34 mm, or 38%.
- Stand 2: 0.56 - 0.34 = 0.22 mm, or 39%.
- Stand 1: 0.34 - 0.26 = 0.08 mm, or 24%.

6.102 Calculate the required roll velocities for each roll in Problem 6.101 in order to maintain a forward slip of (a) zero and (b) 10%.

The forward slip is defined by Eq. (6.24) on p. 291 as:

$$\text{Forward slip (FS)} = \frac{V_f - V_r}{V_r}$$

For the forward slip to be zero, the roll velocity needs to be the final velocity in the rolling operation. From the data given in the figure, the following quantities can be determined:

	Roll velocity	
	FS=0	FS=10%
Stand	(m/s)	(m/s)
1	30	27.3
2	17.7	16.1
3	10.7	9.73
4	6.6	6.0
5	2.6	2.36

Extrusion

6.103 Calculate the force required in direct extrusion of 1100-O aluminum from a diameter of 6 in. to 2 in. Assume that the redundant work is 30% of the ideal work of deformation, and the friction work is 25% of the total work of deformation.

The extrusion ratio is $R = 6^2/2^2 = 9$, and thus the true strain is $\epsilon = \ln(9) = 2.20$. For 1100-O aluminum, we have from Table 2.3 on p. 37, $K = 180$ MPa = 26,000 psi and $n = 0.20$. Therefore, from Eq. (2.60) on p. 71, the average flow stress is

$$\bar{Y} = \frac{K\epsilon^n}{n+1} = \frac{(26,000)(2.20)^{0.20}}{1.20} = 25,360 \text{ psi}$$

The ideal extrusion pressure is, from Eq. (6.54) on p. 310,

$$p = Y \ln R = (25,360) \ln 9 = 55,700 \text{ psi}$$

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The ideal extrusion force is then

$$F = pA = \frac{\pi p d^2}{4} = \frac{\pi(55,700)(6)^2}{4}$$

or $F = 1.57 \times 10^6$ lb. The total force is the sum of the forces for ideal, friction, and redundant deformation. In this case, we can write

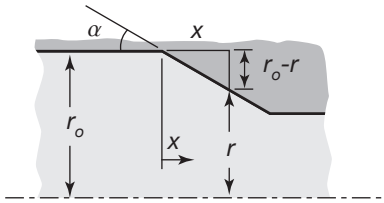
$$F_{\text{total}} = F_{\text{ideal}} + 0.30F_{\text{ideal}} + 0.25F_{\text{total}}$$

Therefore,

$$F_{\text{total}} = 1.73F_{\text{ideal}} = 2.72 \times 10^6 \text{ lb} = 1360 \text{ tons}$$

6.104 Prove Eq. (6.58).

Consider the sketch below for an extrusion operation.



Note that the coordinate x has been measured from the die entry, consistent with Example 6.5. Also, note that the sketch shows one-half of the extrusion operation, as the bottom boundary is a centerline. The initial billet radius is r_o. From the triangle indicated,

$$\tan\alpha = \frac{r_o - r}{x}$$

which is the desired relationship.

6.105 Calculate the theoretical temperature rise in the extruded material in Example 6.6, assuming that there is no heat loss. (See Section 3.9 for information on the physical properties of the material.)

The temperature rise can be calculated from the work done in the process. In Example 6.6 we note that the extrusion force is $F = 3.2 \times 10^6$ lb. Thus, the work done in one inch of travel is $W = 3.2 \times 10^6$ in-lb, and the extruded volume is

$$V = \frac{\pi d^2 l}{4} = \frac{\pi(5)^2(1)}{4} = 19.6 \text{ in}^3$$

For a density of 0.324 lb/in^3 for copper, its weight is (19.6)(0.324) = 6.36 lb. The specific heat for copper is 385 J/kg°C = 0.092 BTU/lb°F. Since 1 BTU = 778 ft-lb = 9336 in.-lb, the work done is equivalent to $3.2 \times 10^6/9336$ = 343 BTU, or 343/6.36 = 54 BTU/lb. Thus, the temperature rise will be 54/0.092 = 590°F, assuming that the process is adiabatic. Note that the final temperature will be 1500 + 590 = 2090°F, which is much above the melting temperature of copper. In practice, extrusion is carried out relatively slowly, so that significant heat can be lost to the environment; also, a 1500°F preheat is very unusual for copper.

6.106 Using the same approach as that shown in Section 6.5 for wire drawing, show that the extrusion pressure is given by the expression

$$p = Y\left(1 + \frac{\tan\alpha}{\mu}\right)\left[1 - \left(\frac{A_o}{A_f}\right)^{\mu\cot\alpha}\right],$$

where A_o and A_f are the original and final workpiece diameters, respectively.

Refer to Fig. 6.61 on p. 321 for a stress element, from which we apply equilibrium in the x-direction as

$$\begin{aligned} 0 &= (\sigma_x + d\sigma_x)\frac{\pi}{4}(D + dD)^2 \\ &\quad -\sigma_x\frac{\pi}{4}D^2 + p\frac{\pi D dx}{\cos\alpha} + \mu p\frac{\pi D dx}{\cos\alpha} \end{aligned}$$

Simplifying and ignoring second-order terms,

$$0 = Dd\sigma_x + 2\sigma_x dD + 2p\left(1 + \frac{\mu}{\tan\alpha}\right)dD$$

From Eq. (2.36) on p. 64, and recognizing that positive pressure indicates negative stress,

$$\sigma_{\max} - \sigma_{\min} = \sigma_x + p = Y$$

Letting $\mu/\tan\alpha = B$, and using this relationship yields

$$\frac{dD}{D} = \frac{d\sigma_x}{2B\sigma_x - 2Y(1+B)}$$

Integrating this equation between the limits D_f and D_o and by noting that at $D = D_o$, $\sigma_x = -\sigma_d$ (because the stress is negative, although the pressure is positive) and at $D = D_f$, $\sigma_x = 0$,

$$\sigma_d = Y\frac{1+B}{B}\left[1 - \left(\frac{D_f}{D_o}\right)^{2B}\right]$$

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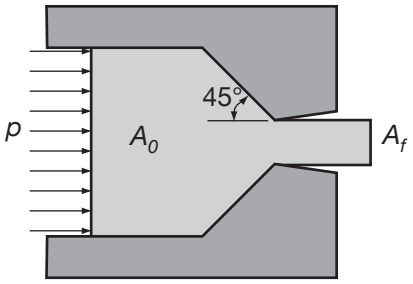
or, noting that $p = \sigma_d$,

$$\begin{aligned} p &= Y\frac{1+B}{B}\left[1-\left(\frac{A_f}{A_o}\right)^B\right] \\ &= Y\left(1+\frac{\tan\alpha}{\mu}\right)\left[1-\left(\frac{A_f}{A_o}\right)^{\mu\cot\alpha}\right] \end{aligned}$$

6.107 Derive Eq. (6.56).

An estimate of the pressure p can be obtained as follows, referring to the figure below for nomenclature.



The total power input, P, with a ram velocity of v_o is

$$P_{\text{input}} = pv_o\left(\frac{\pi D_o^2}{4}\right)$$

The power due to plastic work of deformation is the product of the volume rate of flow and the energy per unit volume. Thus,

$$P_{\text{plastic}} = v_o\left(\frac{\pi D_o^2}{4}\right)(Y)\left[\ln\left(\frac{D_o}{D_f}\right)^2\right]$$

As in the problem statement, let's take the dead zone to imply a 45° die angle as shown, and that the frictional stress is equal to the shear yield stress, $k = Y/2$, of the material. The power dissipated due to friction along the die angle can then be calculated as

$$P_{\text{friction}} = v_o\left(\frac{\pi D_o^2}{\sqrt{2}}\right)\left(\frac{Y}{2}\right)\ln\left(\frac{D_o}{D_f}\right)$$

Equating the power input to the sum of the plastic deformation and friction powers, we obtain

$$\begin{aligned} pv_o\left(\frac{\pi D_o^2}{4}\right) &= v_o\left(\frac{\pi D_o^2}{4}\right)(Y)\left[\ln\left(\frac{D_o}{D_f}\right)^2\right] \\ &\quad + v_o\left(\frac{\pi D_o^2}{\sqrt{2}}\right)\left(\frac{Y}{2}\right)\ln\left(\frac{D_o}{D_f}\right) \end{aligned}$$

or

$$\begin{aligned} p &= 3.41Y\ln\left(\frac{D_o}{D_f}\right) = 1.7Y\ln\left(\frac{D_o}{D_f}\right)^2 \\ &= 1.7Y\ln R \end{aligned}$$

In this analysis, we have neglected the force required to overcome friction at the billet-container interface. Assume that the frictional stress is equal to the shear yield stress of the material, k, we can obtain the additional ram pressure required due to friction, p_f, as

$$p_f\left(\frac{\pi D_o^2}{4}\right) = \pi D_o k L$$

or

$$p_f = k\frac{4L}{D_o} = Y\frac{2L}{D_o}$$

6.108 A planned extrusion operation involves steel at 800°C, with an initial diameter of 100 mm and a final diameter of 20 mm. Two presses, one with a capacity of 20 MN and the other of 10 MN, are available for this operation. Obviously, the larger press requires greater care and more expensive tooling. Is the smaller press sufficient for this operation? If not, what recommendations would you make to allow the use of the smaller press?

For steel at 800°C, $k = 425$ MPa (From Fig. 6.53 on p. 313). The initial and final areas are 0.00785 m^2 and 3.14×10^{-4} m^2, respectively. From Eq. (6.62) on p. 313, the extrusion force required is

$$\begin{aligned} F &= A_o k\ln\left(\frac{A_o}{A_f}\right) \\ &= (0.0078)(425)\ln\left(\frac{0.00785}{3.14\times10^{-4}}\right) \\ &= 10.6 \text{ MN} \end{aligned}$$

Thus, the smaller and easier to use press is not suitable for this operation, but it almost has sufficient capacity. If the extrusion temperature can be increased or if friction can be reduced sufficiently, it may then be possible to use this machine.

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6.109 Estimate the force required in extruding 70-30 brass at 700°C, if the billet diameter is 125 mm and the extrusion ratio is 20.

From Fig. 6.53 on p. 313, k for copper at 700 °C is approximately 180 MPa. Noting that R is 20 and $d_o = 125$ mm $= 0.125$ m; using Eq. (6.62) on p. 313, we find that

$$F = (\pi/4)(0.125)^2(180)(\ln 20) = 6.62 \text{ MN}$$

Drawing

6.110 Calculate the power required in Example 6.7 if the workpiece material is annealed 70-30 brass.

For annealed 70-30 brass we have, from Table 2.3 on p. 37, $K = 895$ MPa and $n = 0.49$. Thus, the average flow stress is

$$\bar{Y} = \frac{(895)(0.466)^{0.49}}{1.49} = 413 \text{ MPa}$$

Since all other quantities are the same as in the example, the power will be

$$P = 12.25\left(\frac{413}{785}\right) = 6.4 \text{ kW}$$

6.111 Using Eq. (6.63), make a plot similar to Fig. 6.63 for the following conditions: $K = 100$ MPa, $n = 0.3$, and $\mu = 0.04$.

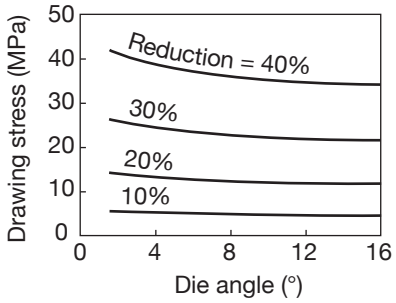
Using Eq. (2.60) on p. 71, we can rewrite Eq. (6.66) on p. 321 as

$$\sigma_d = \left[\frac{K\epsilon^{n+1}}{n+1}\right]\left[1+\frac{\tan\alpha}{\mu}\right]\left[1-\left(\frac{A_f}{A_o}\right)^{\mu\cot\alpha}\right]$$

where ϵ is the final strain. From Eqs. (2.7) on p. 34 and (2.10) on p. 35 it can be shown that $A_f/A_o = e^{-\epsilon}$ and that $\epsilon = -\ln(1-R)$, where R is the reduction. Therefore, the expression becomes:

$$\begin{aligned}\sigma_d &= \left[\frac{K\epsilon^{n+1}}{n+1}\right]\left[1+\frac{\tan\alpha}{\mu}\right]\left[1-(e^{\epsilon})^{\mu\cot\alpha}\right] \\ &= \left[\frac{K\epsilon^{n+1}}{n+1}\right]\left[1+\frac{\tan\alpha}{\mu}\right]\left[1-e^{-\mu\cot\alpha}\right]\end{aligned}$$

This allows construction of the curve given below.



6.112 Using the same approach as that described in Section 6.5 for wire drawing, show that the drawing stress, σ_d, in plane-strain drawing of a flat sheet or plate is given by the expression

$$\sigma_d = Y'\left(1+\frac{\tan\alpha}{\mu}\right)\left[1-\left(\frac{h-f}{h_o}\right)^{\mu\cot\alpha}\right],$$

where h_o and h_f are the original and final thickness, respectively, of the workpiece.

For a plane-strain element, we can apply equilibrium in the x direction as

$$\begin{aligned}0 \quad = \quad & (\sigma_x + d\sigma_x)(h+dh)w - \sigma_x hw \\ & + p\frac{w\,dx}{\cos\alpha} + \mu p\frac{dx}{\cos\alpha}\end{aligned}$$

Simplifying and ignoring second order terms,

$$h\,d\sigma_x + \sigma_x dh + p\left(1+\frac{\mu}{\tan\alpha}\right)dx = 0$$

From Eq. (2.36), and recognizing that positive pressure indicates negative stress,

$$\sigma_{\max} - \sigma_{\min} = \sigma_x + p = Y$$

Letting $\mu/\tan\alpha = B$,

$$\frac{dh}{h} = \frac{d\sigma_x}{2B\sigma_x - 2Y(1+B)}$$

Integrating this equation between the limits h_f and h_o and by noting that at $h = h_o$, $\sigma_x = -\sigma_d$ (because the stress is negative, although the pressure is positive) and at $h = h_f$, $\sigma_x = 0$,

$$\sigma_d = Y\frac{1+B}{B}\left[1-\left(\frac{h_f}{h_o}\right)^B\right]$$

or

$$\sigma_d = Y\left(1+\frac{\tan\alpha}{\mu}\right)\left[1-\left(\frac{h_f}{h_o}\right)^{\mu\cot\alpha}\right]$$

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6.113 Derive an analytical expression for the die pressure in wire drawing, without friction or redundant work, as a function of the instantaneous diameter in the deformation zone.

From Eq. (6.71) on p. 322 we know that the following condition must be satisfied in the deformation zone:

$$\sigma_x + p = Y$$

where the tensile stress σ_x is defined as

$$\sigma_x = Y \ln \left(\frac{D_o}{D_x} \right)^2$$

Consequently,

$$p = Y \left[1 - \ln \left(\frac{D_o}{D_x} \right)^2 \right]$$

Thus, at the die entry, for example, where $\sigma_x = 0$, we have $p = Y$. As we approach the die exit, σ_x increases and hence p decreases. (See Fig. 6.62.)

6.114 A linearly strain-hardening material with a true-stress-true-strain curve $\sigma = 5,000 + 25,000\epsilon$ psi is being drawn into a wire. If the original diameter of the wire is 0.25 in., what is the minimum possible diameter at the exit of the die? Assume that there is no redundant work and that the frictional work is 15% of the ideal work of deformation. (*Hint:* The yield stress of the exiting wire is the point on the true-stress-true-strain curve that corresponds to the total strain that the material has undergone.)

The drawing stress can be expressed in terms of the average flow stress, $\bar{Y}$, as follows:

$$\sigma_d = 1.25 \bar{Y} \epsilon_1$$

For this linearly strain-hardening material, the average flow stress is

$$\begin{aligned} \bar{Y} &= \frac{5,000 + (5,000 + 25,000\epsilon_1)}{2} \\ &= 5,000 + 12,500\epsilon_1 \end{aligned}$$

As the problem states, the yield stress of the exiting wire is

$$Y_1 = 5,000 + 25,000\epsilon_1$$

Equating both expressions, as was done in Eq. (6.71) on p. 322, we obtain

$$5,000 + 25,000\epsilon_1 = \sigma_d = 1.15(5,000 + 12,500\epsilon_1)\epsilon_1$$

Note that the coefficient of 1.15 takes the frictional work into account. This is a quadratic equation with one negative root and one positive root, which is $\epsilon_1 = 1.56$. Thus,

$$\epsilon_1 = \ln \left(\frac{0.25}{D_f} \right)^2 = 1.56$$

This is solved as $D_f = 0.11$ in.

6.115 In Fig. 6.65, assume that the longitudinal residual stress at the center of the rod is -80,000 psi. Using the distortion-energy criterion, calculate the minimum yield stress that this particular steel must have in order to sustain these levels of residual stresses.

This problem requires that (a) elements be taken at different radial positions, (b) the respective residual stresses are determined from the figure, and (c) substituted into the effective stress for the distortion-energy criterion, given by Eq. (2.56) on p. 70. Four locations are checked below.

(a) At the center, we have $\sigma_L = -80,000$ psi, $\sigma_R = -60,000$ psi, and $\sigma_T = -45,000$ psi, thus the effective stress is

$$\begin{aligned} \bar{\sigma} &= \frac{1}{\sqrt{2}} \left[(\sigma_L - \sigma_R)^2 + (\sigma_R - \sigma_T)^2 \right. \\ &\quad \left. + (\sigma_L - \sigma_T)^2 \right]^{1/2} \\ &= 30,500 \text{ psi} \end{aligned}$$

(b) At $R = 0.375$ in., we have $\sigma_L = -5,000$ psi, $\sigma_R = -40,000$ psi and $\sigma_T = -15,000$ psi, and thus the effective stress is 31,000 psi.

(c) At $R = 0.5$ in, we have $\sigma_L = 5,000$ psi, $\sigma_R = -20,000$ psi, and $\sigma_T = -35,000$ psi, and the effective stress is 35,000 psi.

(d) At the surface of the bar, $\sigma_L = 50,000$ psi, $\sigma_R = 0$ and $\sigma_T = 50,000$ psi, and the effective stress is 50,000 psi.

Since the effective stress is equal to the uniaxial stress in a tension test, it can be concluded that this part must have a minimum yield stress of $Y = 50,000$ psi in order to sustain these residual stresses.

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6.116 Derive an expression for the die-separating force in frictionless wire drawing of a perfectly plastic material. Use the same terminology as in the text.

For a straight conical die with an angle α and original and final cross-sectional areas A_o and A_f, respectively, it can be shown that the contact area, A, (in the shape of a truncated cone) is given by

$$A = \frac{A_o - A_f}{\pi \sin \alpha}$$

From the die-pressure curve such as that shown in Fig. 6.62 on p. 322, which can be obtained analytically, we determine an average pressure p_{ave}. Assuming a small die angle, as is generally the case in wire drawing, the radial component of this pressure (i.e., perpendicular to the long axis), is the same as p_{ave}. Further assuming that the die is split in half into two half circles, the die-separating force will act on one-half of the contact area, and thus the force will be

$$F = \frac{(A_o - A_f)\, p_{\text{ave}}}{2\pi \sin \alpha}$$

6.117 A material with a true-stress-true-strain curve $\sigma = 10,000\epsilon^{0.3}$ is used in wire drawing. Assuming that the friction and redundant work compose a total of 50% of the ideal work of deformation, calculate the maximum reduction in cross-sectional area per pass that is possible.

The maximum reduction per pass for a strain-hardening material was derived in Example 6.8. Using a similar approach, the following relationship can be written:

$$K\epsilon_1^n = (1.5)\left(\frac{K\epsilon_1^n}{n+1}\right)\epsilon_1$$

or

$$\epsilon_1 = \frac{n+1}{1.5}$$

Since $n = 0.3$ for this problem, we have $\epsilon_1 = 0.867$. Note that the magnitude of K is not relevant in this problem.

6.118 Derive an expression for the maximum reduction per pass for a material of $\sigma = K\epsilon^n$ assuming that the friction and redundant work contribute a total of 25% to the ideal work of deformation.

This problem requires the same approach as in Problem 6.86 above. Thus, referring to Example 6.8,

$$1.25\epsilon_1 = n + 1$$

and hence

$$\text{Max reduction per pass} = 1 - e^{-(n+1)/1.25}$$

This means that, as expected, the maximum reduction is lower than that obtained for the ideal case in Example 6.8.

6.119 Prove that the true-strain rate, $\dot{\epsilon}$, in drawing or extrusion in plane strain with a wedge-shaped die is given by the expression

$$\dot{\epsilon} = -\frac{2\tan\alpha V_o t_o}{(t_o - 2x\tan\alpha)^2},$$

where α is the die angle, t_o is the original thickness, and x is the distance from die entry (*Hint:* Note that $d\epsilon = dA/A$.)

This problem is very similar to Example 6.5. To avoid confusion between time and thickness variables, lets use h to denote thickness. From geometry in the die gap,

$$\tan\alpha = \frac{(h_o - h)/2}{x}$$

or

$$h = h_o - 2x\tan\alpha.$$

The incremental true strain can be defined as

$$d\epsilon = \frac{dA}{A}$$

where $A = wh$, and w is the (constant) width. Therefore, $dA = wdh$, and hence

$$d\epsilon = \frac{wdh}{wh} = \frac{dh}{h}$$

where $dh = -\tan\alpha\, dx$. We also know that

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = -\frac{2\tan\alpha}{h}\frac{dx}{dt}$$

However, $dx/dt = V$, which is the velocity of the material at any location x in the die. Hence,

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = -\frac{2V\tan\alpha}{h}$$

From constancy of flow rate, we can write

$$V = h_o v_o / h,$$

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and hence,

$$\dot{\epsilon} = -\frac{2V_o h_o \tan\alpha}{h^2} = \frac{2V_o h_o \tan\alpha}{(h_o - 2x\tan\alpha)^2}$$

which is the desired relation. The negative sign is due to the fact that true strain is defined in terms of the cross-sectional area, which decreases as x increases.

6.120 In drawing a strain-hardening material with $n = 0.25$ what should be the percentage of friction plus redundant work, in terms of ideal work, so that the maximum reduction per pass is 63%?

Referring to Example 6.8, we can write the following expression to represent this situation where x is a multiplying factor that includes friction and redundant work in terms of the ideal work of deformation:

$$K\epsilon^n = x\left(\frac{K\epsilon^n}{n+1}\right)\epsilon_1$$

from which we obtain

$$x = \frac{n+1}{\epsilon_1} = \frac{1.25}{\epsilon_1}$$

A reduction of 63% indicates a true strain of $\epsilon_1 = 1$. Hence, $x = 1.25$, and thus the sum of friction and redundant work is 25% of the ideal work.

6.121 A round wire made of a perfectly plastic material with a yield stress of 30,000 psi is being drawn from a diameter of 0.1 to 0.07 in. in a draw die of 15°. Let the coefficient of friction be 0.1. Using both Eqs. (6.61) and (6.66), estimate the drawing force required. Comment on any differences in your answers.

In this problem, $d_o = 0.1$ in, so that the initial cross-sectional area is

$$A_o = \frac{\pi}{4}d_o^2 = \frac{\pi}{4}(0.1 \text{ in.})^2 = 0.00785 \text{ in}^2$$

Similarly, since $d_f = 0.07$ in., $A_f = 0.00385$ in^2. From Eq. (6.61) on p. 313, the force required for drawing is

$$\begin{aligned} F &= Y_{\text{avg}} A_f \ln\frac{A_o}{A_f} \\ &= (30,000)(0.00385)\ln\left(\frac{0.00785}{0.00385}\right) \\ &= 82.3 \text{ lb} \end{aligned}$$

For $\mu = 0.1$ and $\alpha = 15° = 0.262$ radians, Eq. (6.66) on p. 321 yields

$$\begin{aligned} F &= Y_{\text{avg}} A_f \left[\left(1+\frac{\mu}{\alpha}\right)\ln\left(\frac{A_o}{A_f}\right) + \frac{2}{3}\alpha\right] \\ &= (30,000)(0.00385) \\ &\times \left[\left[1+\frac{0.1}{0.262}\right]\ln\left[\frac{0.00785}{0.00385}\right] + \frac{2}{3}(0.262)\right] \end{aligned}$$

or $F = 134$ lb. Note that Eq. (6.61) does not include friction or redundant work effects. Both of these factors will increase the forging force, and this is reflected by these results.

6.122 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

Design

6.123 Forging is one method of producing turbine blades for jet engines. Study the design of such blades and, referring to the relevant technical literature, prepare a step-by-step procedure for making these blades. Comment on the difficulties that may be encountered in this operation.

By the student. A typical sequence would include cutting off a blank from bar stock, block forging, rough forging, finish forging, flash

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removal, inspection, finishing, and cleaning. There may be quenching operations involved, depending on the material and desired properties.

6.124 In comparing some forged parts with cast parts, it will be noted that the same part may be made by either process. Comment on the pros and cons of each process, considering factors such as part size, shape complexity, and design flexibility in the event that a particular design has to be modified.

By the student. Typical answers may address cost issues (forging will be expensive for short production runs), performance (castings may lack ductility), fatigue performance, and microstructure and grain flow.

6.125 Referring to Fig. 6.25, sketch the intermediate steps you would recommend in the forging of a wrench.

This is an open-ended problem, and there would be several acceptable answers. Students should be encouraged to describe the benefits of their die layouts, including their limitations, if any. If bar stock is the input material, an edging operation is useful to distribute material to the ends where the sockets will require extra material. The blocking, finishing, and trimming operations, as sketched in Fig. 6.25 on p. 285, are conceptually the same as those required to make a wrench.

6.126 Review the technical literature, and make a detailed list of the manufacturing steps involved in the manufacture of hypodermic needles.

There are several manufacturers of hypodermic needles, and while each one uses a somewhat different process for production, the basic steps remain the same, including shaping of the needle, plastic-components molding, piece assembly, packaging, and labeling. This is a good topic for a paper by the student.

6.127 Figure 6.48a shows examples of products that can be obtained by slicing long extruded sections into discrete parts. Name several other products that can be made in a similar manner.

By the student. Examples include cookies, pasta, blanks for bearing races, and support brackets of all types. The case study for Chapter 6 shows a support bracket for an automobile axle that was made in this manner. Using the Internet, the students should be able to give numerous other examples.

6.128 Make an extensive list of products that either are made of or have one or more components of (a) wire, (b) very thin wire, and (c) rods of various cross-sections.

By the student. This is an open-ended problem and students should be encouraged to develop their lists based on their experiences and research. Some answers are:

- Wire is commonly found as electrical conductors, wire rope and cable, coat hangers, and nails.
- Very thin wire as integrated circuit packages, communication cable (such as coaxial cable) shielding, and steel wool.
- Rods as axles, bolts and other fasteners, reinforcing bars for concrete.

6.129 Although extruded products are typically straight, it is possible to design dies whereby the extrusion is curved, with a constant radius of curvature. (a) What applications could you think of for such products? (b) Describe your thoughts as to the shape such a die should have in order to produce curved extrusions.

The applications are limited for curved extrusions. Students should be encouraged to develop their own solutions to this problem; some answers are:

(a) For escalators, there are handrails that have a large and constant radius of curvature.

(b) Many architectural shapes are curved.

(c) Bicycle frames and aircraft panels are often constructed by bending an extruded workpiece; if the extruded section is produced pre-bent, then the bending operations would no longer be necessary.

The die shape is difficult to design. If the die cross section is not symmetric, then a curvature

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will naturally develop. However, this would be difficult to control, and it is probably better to incorporate forming rolls that develop a controlled radius of curvature, similar to the guide rolls in ring rolling (see Fig. 6.43 on p. 305).

6.130 Survey the technical literature, and describe the design features of the various roll arrangements shown in Fig. 6.41.

By the student. This is an open-ended problem, and a wide variety of answers are possible based on the student's interpretation of "design features". Students can develop descriptions based on cost, process capability, stiffness of the roll arrangement or the materials rolled.

6.131 The beneficial effects of using ultrasonic vibration to reduce friction in some of the processes were described in this chapter. Survey the technical literature and offer design concepts to apply such vibrations.

By the student. This is a good topic for literature search for a student paper.

6.132 In the Case Study at the end of this chapter, it was stated that there was a significant cost improvement using forgings when compared to the extrusion-based design. List and explain the reasons why you think these cost savings were possible.

There are several acceptable answers to this question. Students should, for example, consider:

(a) By reducing the total number of parts, the tooling and assembly cost is significantly reduced.

(b) Because it is a near net-shape process, machining and finishing costs are significantly reduced.

(c) Material costs may be very different; the extruded alloy, for example, may be more expensive than the forged alloy.

6.133 In the extrusion and drawing of brass tubes for ornamental architectural applications, it is important to produce very smooth surface finishes. List the relevant process parameters and make manufacturing recommendations to produce such tubes.

By the student. This is an open-ended problem, and the students should consider, at a minimum, the following factors:

- A thick lubricant film will generally lead to orange peel.
- A thin lubricant film can lead to wear and material transfer to the tooling and a gradual degradation in the surface produced.
- A polished die surface can produce a smooth workpiece surface; a rough surface cannot.
- The workpiece material used may play a role in the shininess that can be achieved.
- The lubricant can stain the workpiece unless properly formulated.

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Chapter 7

Sheet-Metal Forming Processes

Questions

7.1 Select any three topics from Chapter 2, and, with specific examples for each, show their relevance to the topics described in this chapter.

This is an open-ended problem, and students can develop a wide range of acceptable answers. Some examples are:

- Yield stress and elastic modulus, described in Section 2.2 starting on p. 30, have, for example, applicability to prediction of springback.
- Ultimate tensile strength is important for determining the force required in blanking; see Eq. (7.4) on p. 353.
- Strain-hardening exponent has been referred to throughout this chapter, especially as it relates to the formability of sheet metals.
- Strain is used extensively, most directly in the development of a forming limit diagram, such as that shown in Fig. 7.63a on p. 399.

7.2 Do the same as for Question 7.1, but for Chapter 3.

This is an open-ended problem, and students can develop a wide range of acceptable answers. Consider, for examples:

- Grain size and its effects on strength (Section 3.4 starting on p. 91), as well as the effect of cold working on grain size, (see Section 3.3.4) have a major influence on formability (Section 7.7 on p. 397).
- The material properties of the different materials, described in Section 3.11, indicating materials that can be cold rolling into sheets.

7.3 Describe (a) the similarities and (b) the differences between the bulk-deformation processes described in Chapter 6 and the sheet-metal forming processes described in this chapter.

By the student. The most obvious difference between sheet-metal parts and those made by bulk-deformation processes, described in Chapter 6, is the difference in cross section or thickness of the workpiece. Sheet-metal parts typically have less net volume and are usually much easier to deform or flex. Sheet-metal parts are rarely structural unless they are loaded in tension (because otherwise their small thickness causes them to buckle at relatively low loads) or they are fabricated to produce high section modulus. They can be very large by assembling individual pieces, as in the fuselage of an aircraft. Structural parts that are made by forging and extrusion are commonly loaded in various configurations.

7.4 Discuss the material and process variables that influence the shape of the curve for punch force vs. stroke for shearing, such as that shown in Fig. 7.7 on p. 354, including its height and width.

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The factors that contribute to the punch force and how they affect this force are:

(a) the shear strength of the material and its strain-hardening exponent; they increase the force,

(b) the area being sheared and the sheet thickness; they increase the force and the stroke,

(c) the area that is being burnished by rubbing against the punch and die walls; it increases the force, and

(d) parameters such as punch and die radii, clearance, punch speed, and lubrication.

7.5 Describe your observations concerning Figs. 7.5 and 7.6.

The student should comment on the magnitude of the deformation zone in the sheared region, as influenced by clearance and speed of operation, and its influence on edge quality and hardness distribution throughout the edge. Note the higher temperatures observed in higher-speed shearing. Other features depicted in Fig. 7.5 on p. 352 should also be commented upon.

7.6 Inspect a common paper punch and comment on the shape of the tip of the punch as compared with those shown in Fig. 7.12.

By the student. Note that most punches are unlike those shown in Fig. 7.12 on p. 346; they have a convex curved shape.

7.7 Explain how you would estimate the temperature rise in the shear zone in a shearing operation.

Refer to Fig. 7.6 on p. 353 and note that we can estimate the shear strain γ to which the shearing zone is subjected. This is done by considering the definition of simple shear, given by Eq. (2.2) on p. 30, and comparing this deformation with the deformation of grid patterns in the figure. Then refer to the shear stress-shear strain curve of the particular material being sheared, and obtain the area under the curve up to that particular shear strain, just as we have done in various other problems in the text. This will give the shearing energy per unit volume. We then refer to Eq. (2.65) on p. 73 and knowing the physical properties of the material, calculate the theoretical temperature rise.

7.8 As a practicing engineer in manufacturing, why would you be interested in the shape of the curve shown in Fig. 7.7? Explain.

The shape of the curve in Fig. 7.7 on p. 354 will give us the following information:

(a) height of the curve: the maximum punch force,

(b) area under the curve: the energy required for this operation,

(c) horizontal magnitude of the curve: the punch travel required to complete the shearing operation.

It is apparent that all this information should be useful to a practicing engineer in regard to the machine tool and the energy level required.

7.9 Do you think the presence of burrs can be beneficial in certain applications? Give specific examples.

The best example generally given for this question is mechanical watch components, such as small gears whose punched holes have a very small cross-sectional area to be supported by the spindle or shaft on which it is mounted. The presence of a burr enlarges this contact area and, thus, the component is better supported. As an example, note how the burr in Fig. 7.5 on p. 352 effectively increases the thickness of the sheet.

7.10 Explain why there are so many different types of tool and die materials used for the processes described in this chapter.

By the student. Among several reasons are the level of stresses and type of loading involved (such as static or dynamic), relative sliding between components, temperature rise, thermal cycling, dimensional requirements and size of workpiece, frictional considerations, wear, and economic considerations.

7.11 Describe the differences between compound, progressive, and transfer dies.

This topic is explained in Section 7.3.2 starting on p. 356. Basically, a compound die performs

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several operations in one stroke at one die station. A progressive die performs several operations, one per stroke, at one die station (more than one stroke is necessary). A transfer die performs one operation at one die station.

7.12 It has been stated that the quality of the sheared edges can influence the formability of sheet metals. Explain why.

In many cases, sheared edges are subjected to subsequent forming operations, such as bending, stretching, and stretch flanging. As stated in Section 7.3 starting on p. 351, rough edges will act as stress raisers and cold-worked edges (see Fig. 7.6b on p. 353) may not have sufficient ductility to undergo severe tensile strains developed during these subsequent operations.

7.13 Explain why and how various factors influence springback in bending of sheet metals.

Plastic deformation (such as in bending processes) is unavoidably followed by elastic recovery, since the material has a finite elastic modulus (see Fig. 2.3 on p. 33). For a given elastic modulus, a higher yield stress results in a greater springback because the elastic recovery strain is greater. A higher elastic modulus with a given yield stress will result in less elastic strain, thus less springback. Equation (7.10) on p. 364 gives the relation between radius and thickness. Thus, increasing bend radius increases springback, and increasing the sheet thickness reduces the springback.

7.14 Does the hardness of a sheet metal have an effect on its springback in bending? Explain.

Recall from Section 2.6.8 on p. 54 that hardness is related to strength, such as yield stress as shown in Fig. 2.24 on p. 55. Referring to Eq. (7.10) on p. 364 , also note that the yield stress, Y, has a significant effect on springback. Consequently, hardness is related to springback. Note that hardness does not affect the elastic modulus, E, given in the equation.

7.15 As noted in Fig. 7.16, the state of stress shifts from plane stress to plane strain as the ratio of length-of-bend to sheet thickness increases. Explain why.

This situation is somewhat similar to rolling of sheet metal where the wider the sheet, the closer it becomes to the plane-strain condition. In bending, a short length in the bend area has very little constraint from the unbent regions, hence the situation is one of basically plane stress. On the other hand, the greater the length, the more the constraint, thus eventually approaching the state of plane strain.

7.16 Describe the material properties that have an effect on the relative position of the curves shown in Fig. 7.19.

Observing curves (a) and (c) in Fig. 7.19 on p. 364, note that the former is annealed and the latter is heat treated. Since these are all aluminum alloys and, thus, have the same elastic modulus, the difference in their springback is directly attributable to the difference in their yield stress. Likewise, comparing curves (b), (d), and (e), note that they are all stainless steels and, thus, have basically the same elastic modulus. However, as the amount of cold work increases (from annealed to half-hard condition), the yield stress increases significantly because austenitic stainless steels have a high n value (see Table 2.3 on p. 37). Note that these comparisons are based on the same R/T ratio.

7.17 In Table 7.2, we note that hard materials have higher R/t ratios than soft ones. Explain why.

This is a matter of the ductility of the material, particularly the reduction in area, as depicted by Eqs. (7.6) on p. 361 and (7.7) on p. 362. Thus, hard material conditions mean lower tensile reduction and, therefore, higher R/T ratios. In other words, for a constant sheet thickness, T, the bend radius, R, has to be larger for higher bendability.

7.18 Why do tubes have a tendency to buckle when bent? Experiment with a straight soda straw, and describe your observations.

Recall that, in bending of any section, one-half of the cross section is under tensile stresses and the other half under compressive stresses. Also, compressing a column tends to buckle it, depending on its slenderness. Bending of a tube subjects it to the same state of stress, and since

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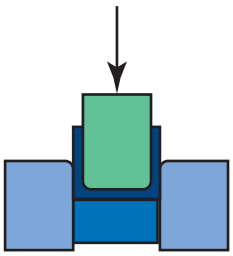
most tubes have a rather small thickness compared to their diameter, there is a tendency for the compression side of the tube to buckle. Thus, the higher the diameter-to-thickness ratio, the greater the tendency to buckle during bending.

7.19 Based on Fig. 7.22, sketch and explain the shape of a U-die used to produce channel-shaped bends.

The design would be a mirror image of the sketches given in Fig. 7.22b on p. 356 along a vertical axis. For example, the image below was obtained from S. Kalpakjian, *Manufacturing Processes for Engineering Materials*, 1st ed., 1984, p. 415.



7.20 Explain why negative springback does not occur in air bending of sheet metals.

The reason is that in air bending (shown in Fig. 7.24a on p. 368), the situation depicted in Fig. 7.20 on p. 365 cannot develop. Bending in the opposite direction, as depicted between stages (b) and (c), cannot occur because of the absence of a lower "die" in air bending.

7.21 Give examples of products in which the presence of beads is beneficial or even necessary.

The student is encouraged to observe various household products and automotive components to answer this question. For example, along the rim of many sheet-metal cooking pots, a bead is formed to confine the burr and prevent cuts from handling the pot. Also, the bead increases the section odulus, making th pot stiffer in the diametral direction.

7.22 Assume that you are carrying out a sheet-forming operation and you find that the material is not sufficiently ductile. Make suggestions to improve its ductility.

By the student. This question can be answered in a general way by describing the effects of temperature, state of stress, surface finish, deformation rate, etc., on the ductility of metals.

7.23 In deep drawing of a cylindrical cup, is it always necessary that there to be tensile circumferential stresses on the element in the cup wall, a shown in Fig. 7.50b? Explain.

The reason why there may be tensile hoop stresses in the already formed cup in Fig. 7.50b on p. 388 is due to the fact that the cup can be tight on the punch during drawing. That is why they often have to be stripped from the punch with a stripper ring, as shown in Fig. 7.49a on p. 387. There are situations, however, whereby, depending on material and process parameters, the cup is sufficiently loose on the punch so that there are no tensile hoop stresses developed.

7.24 When comparing hydroforming with the deep-drawing process, it has been stated that deeper draws are possible in the former method. With appropriate sketches, explain why.

The reason why deeper draws can be obtained by the hydroform process is that the cup being formed is pushed against the punch by the hydrostatic pressure in the dome of the machine (see Fig. 7.34 on p. 375). This means that the cup is traveling with the punch in such a way that the longitudinal tensile stresses in the cup wall are reduced, by virtue of the frictional resistance at the interface. With lower tensile stresses, deeper draws can be made, i.e., the blank diameter to punch diameter ratio can be greater. A similar situation exists in drawing of tubes through dies with moving or stationary mandrels, as discussed in O. Hoffman and G. Sachs, *Introduction to the Theory of Plasticity for Engineers*, McGraw-Hill, 1953, Chapter 17.

7.25 We note in Fig. 7.50a that element A in the flange is subjected to compressive circumferential (hoop) stresses. Using a simple free-body diagram, explain why.

This is shown simply by a free-body diagram, as illustrated below. Note that friction between the blank and die and the blankholder also contribute to the magnitude of the tensile stress.

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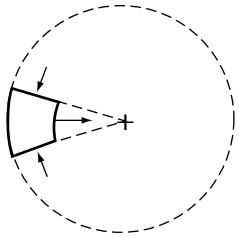

7.26 From the topics covered in this chapter, list and explain specifically several examples where friction is (a) desirable and (b) not desirable.

By the student. This is an open-ended problem. For example, friction is desirable in rolling, but it is generally undesirable for most forming operations.

7.27 Explain why increasing the normal anisotropy, R, improves the deep drawability of sheet metals.

The answer is given at the beginning of Section 7.6.1. The student is encouraged to elaborate further on this topic.

7.28 What is the reason for the negative sign in the numerator of Eq. (7.21)?

The negative sign in Eq. (7.21) on p. 392 is simply for the purpose of indicating the degree of planar anisotropy of the sheet. Note that if the R values in the numerator are all equal, then $\Delta R = 0$, thus indicating no planar anisotropy, as expected.

7.29 If you could control the state of strain in a sheet-forming operation, would you rather work on the left or the right side of the forming-limit diagram? Explain.

By inspecting Fig. 7.63a on p. 399, it is apparent that the left side has a larger safe zone than the right side, under each curve. Consequently, it is more desirable to work in a state of strain on the left side.

7.30 Comment on the effect of lubrication of the punch surfaces on the limiting drawing ratio in deep drawing.

Referring to Fig. 7.49 on p. 387, note that lubricating the punch is going to increase the longitudinal tensile stress in the cup being formed (Fig. 7.50b on p. 388). Thus, deep drawability will decrease, hence the limited drawing ratio will also decrease. Conversely, not lubricating the punch will allow the cup to travel with the punch, thus reducing the longitudinal tensile stress.

7.31 Comment on the role of the size of the circles placed on the surfaces of sheet metals in determining their formability. Are square grid patterns, as shown in Fig. 7.65, useful? Explain.

We note in Fig. 7.65 on p. 400 that, obviously, the smaller the inscribed circles, the more accurately we can determine the magnitude and location of strains on the surface of the sheet being formed. These are important considerations. Note in the figure, for example, how large the circles are as compared with the size of the crack that has developed. As for square grid patters, their distortion will not give a clear and obvious indication of the major and minor strains. Although they can be determined from geometric relationships, it is tedious work to do so.

7.32 Make a list of the independent variables that influence the punch force in deep drawing of a cylindrical cup, and explain why and how these variables influence the force.

The independent variables are listed at the beginning of Section 7.6.2. The student should be able to explain why each variable influences the punch force, based upon a careful reading of the materials presented. The following are sample answers, but should not be considered the only acceptable ones.

(a) The blank diameter affects the force because the larger the diameter, the greater the circumference, and therefore the greater the volume of material to be deformed.

(b) The clearance, c, between the punch and die directly affects the force; the smaller the clearance the greater the thickness reduction and hence the work involved.

(c) The workpiece properties of yield strength and strain-hardening exponent affect the force because as these increase, greater forces will be required to cause deformation beyond yielding.

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(d) Blank thickness also increases the volume deformed, and therefore increases the force.

(e) The blankholder force and friction affect the punch force because they restrict the flow of the material into the die, hence additional energy has to be supplied to overcome these forces.

7.33 Explain why the simple tension line in the forming-limit diagram in Fig. 7.63a states that it is for $R = 1$, where R is the normal anisotropy of the sheet.

Note in Fig. 7.63a on p. 399 that the slope for simple tension is 2, which is a reflection of the Poisson's ratio in the plastic range. In other words, the ratio of minor strain to major strain is -0.5. Recall that this value is for a material that is homogeneous and isotropic. Isotropy means that the R value must be unity.

7.34 What are the reasons for developing forming-limit diagrams? Do you have any specific criticisms of such diagrams? Explain.

The reasons for developing the FLD diagrams are self-evident by reviewing Section 7.7.1. Criticisms pertain to the fact that:

(a) the specimens are still somewhat idealized,

(b) frictional conditions are not necessarily representative of actual operations, and

(c) the effects of bending and unbending during actual forming operations, the presence of beads, die surface conditions, etc., are not fully taken into account.

7.35 Explain the reasoning behind Eq. (7.20) for normal anisotropy, and Eq. (7.21) for planar anisotropy, respectively.

Equation (7.20) on p. 391 represents an average R value by virtue of the fact that all directions (at 45^circ intervals) are taken into account.

7.36 Describe why earing occurs. How would you avoid it? Would ears serve any useful purposes? Explain.

Earing, described in Section 7.6.1 on p. 394, is due to the planar anisotropy of the sheet metal. Consider a round blank and a round die cavity; if there is planar anisotropy, then the blank will have less resistance to deformation in some directions compared to others, and will thin more in directions of greater resistance, thus developing ears.

7.37 It was stated in Section 7.7.1 that the thicker the sheet metal, the higher is its curve in the forming-limit diagram. Explain why.

In forming-limit diagrams, increasing thickness tends to raise the curves. This is because the material is capable of greater elongations since there is more material to contribute to length.

7.38 Inspect the earing shown in Fig. 7.57, and estimate the direction in which the blank was cut.

The rolled sheet is stronger in the direction of rolling. Consequently, that direction resists flow into the die cavity during deep drawing and the ear is at its highest position. In Fig. 7.57 on p. 394, the directions are at about $\pm 45°$ on the photograph.

7.39 Describe the factors that influence the size and length of beads in sheet-metal forming operations.

The size and length of the beads depends on the particular blank shape, die shape, part depth, and sheet thickness. Complex shapes require careful placing of the beads because of the importance of sheet flow control into the desired areas in the die.

7.40 It is known that the strength of metals depends on their grain size. Would you then expect strength to influence the R value of sheet metals? Explain.

It seen from the Hall-Petch Eq. (3.8) on p. 92 that the smaller the grain size, the higher the yield strength of the metal. Since grain size also influences the R values, we should expect that there is a relationship between strength and R values.

7.41 Equation (7.23) gives a general rule for dimensional relationships for successful drawing without a blankholder. Explain what would happen if this limit is exceeded.

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If this limit is exceeded, the blank will begin to wrinkle and we will produce a cup that has wrinkled walls.

7.42 Explain why the three broken lines (simple tension, plane strain, and equal biaxial stretching) in Fig. 7.63a have those particular slopes.

Recall that the major and minor strains shown in Fig. 7.63 on p. 399 are both in the plane of the sheet. Thus, the simple tension curve has a negative slope of 2:1, reflecting the Poisson's ratio effect in plastic deformation. In other words, the minor strain is one-half the major strain in simple tension, but is opposite in sign. The plane-strain line is vertical because the minor strain is zero in plane-strain stretching. The equal (balanced) biaxial curve has to have a 45° slope because the tensile strains are equal to each other. The curve at the farthest left is for pure shear because, in this state of strain, the tensile and compressive strains are equal in magnitude (see also Fig. 2.20 on p. 49).

7.43 Identify specific parts on a typical automobile, and explain which of the processes described in Chapters 6 and 7 can be used to make those part. Explain your reasoning.

By the student. Some examples would be:

(a) Body panels are obtained through sheet-metal forming and shearing.

(b) Frame members (only visible when looked at from underneath) are made by roll forming.

(c) Ash trays are made from stamping, combined with shearing.

(d) Oil pans are classic examples of deep-drawn parts.

7.44 It was stated that bendability and spinnability have a common aspect as far as properties of the workpiece material are concerned. Describe this common aspect.

By comparing Fig. 7.15b on p. 360 on bendability and Fig. 7.39 on p. 379 on spinnability, we note that maximum bendability and spinnability are obtained in materials with approximately 50% tensile reduction of area. Any further increase in ductility does not improve these forming characteristics.

7.45 Explain the reasons that such a wide variety of sheet-forming processes has been developed and used over the years.

By the student, based on the type of products that are made by the processes described in this chapter. This is a demanding question; ultimately, the reasons that sheet-forming processes have been developed are due to demand and economic considerations.

7.46 Make a summary of the types of defects found in sheet-metal forming processes, and include brief comments on the reason(s) for each defect.

By the student. Examples of defects include (a) fracture, which results from a number of reasons including material defects, poor lubrication, etc; (b) poor surface finish, either from scratching attributed to rough tooling or to material transfer to the tooling or orange peel; and (c) wrinkles, attributed to in-plane compressive stresses during forming.

7.47 Which of the processes described in this chapter use only one die? What are the advantages of using only one die?

The simple answer is to restrict the discussion to rubber forming (Fig. 7.33 on p. 375) and hydroforming (Fig. 7.34 on p. 375), although explosive forming or even spinning could also be discussed. The main advantage is that only one tool needs to be made or purchased, as opposed to two matching dies for conventional pressworking and forming operations.

7.48 It has been suggested that deep drawability can be increased by (a) heating the flange and/or (b) chilling the punch by some suitable means. Comment on how these methods could improve drawability.

Refering to Fig. 7.50, we note that:

(a) heating the flange will lower the strength of the flange and it will take less energy to deform element A in the figure, thus it will require less punch force. This will reduce the tendency for cup failure and thus improve deep drawability.

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(b) chilling the punch will increase the strength of the cup wall, hence the tendency for cup failure by the longitudinal tensile stress on element B will be less, and deep drawability will be improved.

7.49 Offer designs whereby the suggestions given in Question 7.48 can be implemented. Would production rate affect your designs? Explain.

This is an open-ended problem that requires significant creativity on the part of the student. For example, designs that heat the flange may involve electric heating elements in the blankholder and/or the die, or a laser as heat source. Chillers could be incorporated in the die and the blankholder, whereby cooled water is circulated through passages in the tooling.

7.50 In the manufacture of automotive-body panels from carbon-steel sheet, stretcher strains (Lueder's bands) are observed, which detrimentally affect surface finish. How can stretcher strains be eliminated?

The basic solution is to perform a temper rolling pass shortly before the forming operation, as described in Section 6.3.4 starting on p. 301. Another solution is to modify the design so that Lueders bands can be moved to regions where they are not objectionable.

7.51 In order to improve its ductility, a coil of sheet metal is placed in a furnace and annealed. However, it is observed that the sheet has a lower limiting drawing ratio than it had before being annealed. Explain the reasons for this behavior.

When a sheet is annealed, it becomes less anisotropic; the discussion of LDR in Section 7.6.1 would actually predict this behavior. The main reason is that, when annealed, the material has a high strain-hardening exponent. As the flange becomes subjected to increasing plastic deformation (as the cup becomes deeper), the drawing force increases. If the material is not annealed, then the flange does not strain harden as much, and a deeper container can be drawn.

7.52 What effects does friction have on a forming-limit diagram? Explain.

By the student. Friction can have a strong effect on formability. High friction will cause localized strains, so that formability is decreased. Low friction allows the sheet to slide more easily over the die surfaces and thus distribute the strains more evenly.

7.53 Why are lubricants generally used in sheet-metal forming? Explain, giving examples.

Lubricants are used for a number of reasons. Mainly, they reduce friction, and this improves formability as discussed in the answer to Problem 7.52. As an example of this, lightweight oils are commonly applied in stretch forming for automotive body panels. Another reason is to protect the tooling from the workpiece material; an example is the lubricant in can ironing where aluminum pickup can foul tooling and lead to poor workpiece surfaces. The student is encouraged to pursue other reasons. (See also Section 4.4 starting on p. 138.)

7.54 Through changes in clamping, a sheet-metal forming operation can allow the material to undergo a negative minor strain in the FLD. Explain how this effect can be advantageous.

As can be seen from Fig. 7.63a on p. 399, if a negative minor strain can be induced, then a larger major strain can be achieved. If the clamping change is less restrictive in the minor strain direction, then the sheet can contract more in this direction and thus allow larger major strains to be achieved without failure.

7.55 How would you produce the parts shown in Fig. 7.35b other than by tube hydroforming?

By the student. The part could be produced by welding sections of tubing together, or by a suitable casting operation. Note that in either case production costs are likely to be high and production rates low.

7.56 Give three examples each of sheet metal parts that (a) can and (b) cannot be produced by incremental forming operations.

By the student. This is an open-ended problem that requires some consideration and creativity on the part of the student. Consider, for example:

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(a) Parts that can be formed are light fixtures, automotive body panels, kitchen utensils, and hoppers.

(b) Incremental forming is a low force operation with limited size capability (limited to the workspace of the CNC machine performing the operation). Examples of parts that cannot be incrementally formed are spun parts where the thickness of the sheet is reduced, or very large parts such as the aircraft wing panels in Fig. 7.30 on p. 372. Also, continuous parts such as roll-formed sections and parts with reentrant corners such as those with hems or seams are not suitable for incremental forming.

7.57 Due to preferred orientation (see Section 3.5), materials such as iron can have higher magnetism after cold rolling. Recognizing this feature, plot your estimate of LDR vs. degree of magnetism.

By the student. There should be a realization that there is a maximum magnetism with fully aligned grains, and zero magnetism with fully random orientations. The shape of the curve between these extremes is not intuitively obvious, but a linear relationship can be expected.

7.58 Explain why a metal with a fine-grain microstructure is better suited for fine blanking than a coarse-grained metal.

A fine-blanking operation can be demanding; the clearances are very low, the tooling is elaborate (including stingers and a lower pressure cushion), and as a result the sheared surface quality is high. The sheared region (see Fig. 7.6 on p. 353) is well defined and constrained to a small volume. It is beneficial to have many grain boundaries (in the volume that is fracturing) in order to have a more uniform and controlled crack.

7.59 What are the similarities and differences between roll forming described in this chapter and shape rolling in Chapter 6?

By the student. Consider, for example:

(a) Similarities include the use of rollers to control the material flow, the production of parts with constant cross section, and similar production rates.

(b) Differences include the mode of deformation (bulk strain vs. bending and stretching of sheet metal), and the magnitude of the associated forces and torques.

7.60 Explain how stringers can adversely affect bendability. Do they have a similar effects on formability?

Stingers, as shown in Fig. 7.17, have an adverse affect on bendability when they are oriented transverse to the bend direction. The basic reason is that stringers are hard and brittle inclusions in the sheet metal and thus serve as stress concentrations. If they are transverse to this direction, then there is no stress concentration.

7.61 In Fig. 7.56, the caption explains that zinc has a high c/a ratio, whereas titanium has a low ratio. Why does this have relevance to limiting drawing ratio?

This question can be best answered by referring to Fig. 3.4 and reviewing the discussion of slip in Section 3.3. For titanium, the c/a ratio in its hcp structure is low, hence there are only a few slip systems. Thus, as grains become oriented, there will be a marked anisotropy because of the highly anisotropic grain structure. On the other hand, with magnesium, with a high c/a ratio, there are more slip systems (outside of the close-packed direction) active and thus anisotropy will be less pronounced.

7.62 Review Eqs. (7.12) through (7.14) and explain which of these expressions can be applied to incremental forming.

By the student. These equations are applicable because the deformation in incremental forming is highly localized. Note that the strain relationships apply to a shape as if a mandrel was present.

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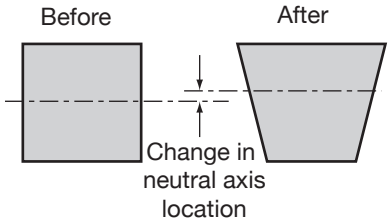
Problems

7.63 Referring to Eq. (7.5), it is stated that actual values of e_o are significantly higher than values of e_i, due to the shifting of the neutral axis during bending. With an appropriate sketch, explain this phenomenon.

The shifting of the neutral axis in bending is described in mechanics of solids texts. Briefly, the outer fibers in tension shrink laterally due to the Poisson' effect (see Fig. 7.17c), and the inner fibers expand. Thus, the cross section is no longer rectangular but has the shape of a trapezoid, as shown below. The neutral axis has to shift in order to satisfy the equilibrium equations regarding forces and internal moments in bending.



7.64 Note in Eq. (7.11) that the bending force is a function of t^2. Why? (*Hint:* Consider bending-moment equations in mechanics of solids.)

This question is best answered by referring to formulas for bending of beams in the study of mechanics of solids. Consider the well-known equation

$$\sigma = \frac{Mc}{I}$$

where c is directly proportional to the thickness, and I is directly proportional to the third power of thickness. For a cantilever beam, the force can be taken as $F = M/L$, where L is the moment arm. For plastic deformation, σ is the material flow stress. Therefore:

$$\sigma = \frac{Mc}{I} \propto \frac{FLt}{t^3}$$

and thus,

$$F \propto \frac{\sigma t^2}{L}$$

7.65 Calculate the minimum tensile true fracture strain that a sheet metal should have in order to be bent to the following R/t ratios: (a) 0.5, (b) 2, and (c) 4. (See Table 7.2.)

To determine the true strains, we first refer to Eq. (7.7) to obtain the tensile reduction of area as a function of R/T as

$$\frac{R}{T} = \frac{60}{r} - 1$$

or

$$r = \frac{60}{(R/T + 1)}$$

The strain at fracture can be calculated from Eq. (2.10) as

$$\begin{aligned} \epsilon_f &= \ln\left(\frac{A_o}{A_f}\right) = \ln\left(\frac{100}{100 - r}\right) \\ &= \ln\left[\frac{100}{100 - \left(\dfrac{60}{(R/T + 1)}\right)}\right] \end{aligned}$$

This equation gives for $R/T = 0.5$, and ϵ_f is found to be 0.51. For $R/T = 2$, we have $\epsilon_f = 0.22$, and for $R/T = 4$, $\epsilon_f = 0.13$.

7.66 Estimate the maximum bending force required for a $\frac{1}{8}$-in. thick and 12-in. wide Ti-5Al-2.5Sn titanium alloy in a V-die with a width of 6 in.

The bending force is calculated from Eq. (7.11). Note that Section 7.4.3 states that k takes a range from 1.2 to 1.33 for a V-die, so an average value of $k = 1.265$ will be used. From Table 3.14, we find that UTS=860 MPa = 125,000 psi. Also, the problem statement gives us $L = 12$ in., $T = \frac{1}{8}$ in $= 0.125$ in, and $W = 6$ in. Therefore, Eq. (7.11) gives

$$\begin{aligned} F_{\max} &= k\frac{(UTS)LT^2}{W} \\ &= (1.265)\frac{(125,000)(12)(0.125)^2}{6} \\ &= 4940 \text{ lb} \end{aligned}$$

7.67 In Example 7.4, calculate the work done by the force-distance method, i.e., work is the integral

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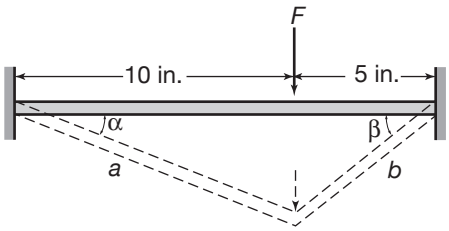
product of the vertical force, F, and the distance it moves.

Let the angle opposite to α be designated as β as shown.



Since the tension in the bar is constant, the force F can be expressed as

$$F = T\left(\sin\alpha + \sin\beta\right)$$

where T is the tension and is given by

$$T = \sigma A = \left(100,000\epsilon^{0.3}\right) A$$

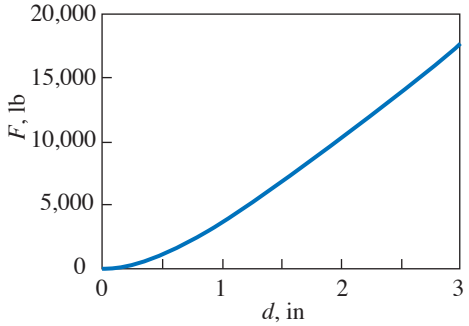
The area is the actual cross section of the bar at any position of the force F, obtained from volume constancy. We also know that the true strain in the bar, as it is being stretched, is given by

$$\epsilon = \ln\left(\frac{a+b}{15}\right)$$

Using these relationships, we can plot F vs. d. Some of the points on the curve are:

α (°)	d (in.)	ϵ	T (kip)	F (kip)
5	0.87	0.008	11.5	2.98
10	1.76	0.03	16.9	8.58
15	2.68	0.066	20.7	15.1
20	3.64	0.115	23.3	21.7

The curve is plotted as follows and the integral is evaluated (from a graphing software package) as 34,600 in-lb.



7.68 What would be the answer to Example 7.4 if the tip of the force, F, were fixed to the strip by some means, thus maintaining the lateral position of the force? (*Hint:* Note that the left portion of the strip will now be strained more than the right portion.)

In this problem, the work done must be calculated for each of the two members. Thus, for the left side, we have

$$a = \frac{10 \text{ in.}}{\cos 20^\circ} = 10.64 \text{ in.}$$

where the true strain is

$$\epsilon_a = \ln\left(\frac{10.64}{10}\right) = 0.062$$

It can easily be shown that the angle β corresponding to $\alpha = 20^\circ$ is 36°. Hence, for the left portion,

$$b = \frac{(5in.)}{\cos 36^\circ} = 6.18 \text{ in.}$$

and the true strain is

$$\epsilon_b = \ln\left(\frac{6.18}{5}\right) = 0.21$$

Thus, the total work done is

$$\begin{aligned} W &= (10)(0.5)(100,000)\int_0^{0.062} \epsilon^{0.3}\, d\epsilon \\ &\quad +(5)(0.5)(100,000)\int_0^{0.21} \epsilon^{0.3}\, d\epsilon \\ &= 35,700 \text{ in.-lb} \end{aligned}$$

7.69 Calculate the magnitude of the force F in Example 7.4 for $\alpha = 30^\circ$.

See the solution to Problem 7.67 for the relevant equations. For $\alpha = 30$,

$$d = (10 \text{ in.})\tan\alpha = 5.77 \text{ in.}$$

also, $T = 25.7$ kip and $F = 32.2$ kip.

7.70 How would the force in Example 7.4 vary if the workpiece were made of a perfectly-plastic material?

We refer to the solution to Problem 7.67 and combine the equations for T and F,

$$F = \sigma A\left(\sin\alpha + \sin\beta\right)$$

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Whereas Problem 7.67 pertained to a strain-hardening material, in this problem the true stress σ is a constant at Y regardless of the magnitude of strain. Inspecting the table in the answer, we note that as the downward travel, d, increases, F must increase as well because the rate of increase in the term $(\sin\alpha + \sin\beta)$ is higher than the rate of decrease of the cross-sectional area. However, F will not rise as rapidly as it does for a strain-hardening material because σ is constant.

Note that an equation such as Eq. (2.60) on p. 71 can give an effective yield stress for a strain-hardening material. If such a value is used, F would have a large value for zero deflection. The effect is that the curve is shifted upwards and flattened. The integral under the curve would be the same.

7.71 Calculate the press force required in punching 0.5-mm-thick 5052-O aluminum foil in the shape of a square hole 30 mm on each side.

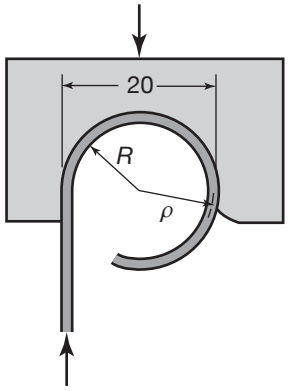
The approach is the same as in Example 7.1. The press force is given by Eq. (7.4) on p. 353:

$$F_{\max} = 0.7(\text{UTS})(t)(L)$$

For this problem, UTS=190 MPa (see Table 3.7 on p. 116). The distance L is 4(30 mm) = 120 mm, and the thickness is given as t=0.5 mm. Therefore,

$$F_{\max} = 0.7(190)(0.5)(120) = 7980 \text{ N}$$

7.72 A straight bead is being formed on a 1-mm-thick aluminum sheet in a 20-mm-diameter die cavity, as shown in the accompanying figure. (See also Fig. 7.25a.) Let $Y = 150$ MPa. Considering springback, calculate the outside diameter of the bead after it is formed and unloaded from the die.



For this aluminum sheet, we have $Y = 150$ MPa and $E = 70$ GPa (see Table 2.1 on p. 32). Using Eq. (7.10) on p. 364 for springback, and noting that the die has a diameter of 20 mm and the sheet thickness is $T = 1$ mm, the initial bend radius is

$$R_i = \frac{20 \text{ mm}}{2} - 1 \text{ mm} = 9 \text{ mm}$$

Note that

$$\frac{R_i Y}{ET} = \frac{(0.009)(150)}{(70,000)(0.001)} = 0.0193$$

Therefore, Eq. (7.10) on p. 364 yields

$$\begin{aligned} \frac{R_i}{R_f} &= 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1 \\ &= 4(0.0193)^3 - 3(0.0193) + 1 \\ &= 0.942 \end{aligned}$$

and,

$$R_f = \frac{R_i}{0.942} = \frac{9 \text{ mm}}{0.942} = 9.55 \text{ mm}$$

Hence, the final outside diameter will be

$$\begin{aligned} \text{OD} &= 2R_f + 2T \\ &= 2(9.55 \text{ mm}) + 2(1 \text{ mm}) \\ &= 21.1 \text{ mm} \end{aligned}$$

7.73 Inspect Eq. (7.10) and substituting in some numerical values, show whether the first term in the equation can be neglected without significant error in calculating springback.

As an example, consider the situation in Problem 7.72 where it was shown that

$$\frac{R_i Y}{ET} = \frac{(0.009)(150)}{(70,000)(0.001)} = 0.0193$$

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Consider now the right side of Eq. (7.10) on p. 364 :

$$4\left(\frac{R_iY}{ET}\right)^3 - 3\left(\frac{R_iY}{ET}\right) + 1$$

Substituting the value from Problem 7.72,

$$4(0.0193)^3 - 3(0.0193) + 1$$

which is

$$2.88 \times 10^{-5} - 0.058 + 1$$

Clearly, the first term is small enough to ignore, which is the typical case.

7.74 In Example 7.5, calculate the amount of TNT required to develop a pressure of 10,000 psi on the surface of the workpiece. Use a standoff of one foot.

Using Eq. (7.17) on p. 381 we can write

$$p = K\left(\frac{\sqrt[3]{W}}{R}\right)^a$$

Solving for W,

$$\begin{aligned} W &= \left(\frac{p}{K}\right)^{3/a} R^3 \\ &= \left(\frac{10000}{21600}\right)^{3/1.15} (1)^3 = 0.134 \text{ lb} \end{aligned}$$

7.75 Estimate the limiting drawing ratio (LDR) for the materials listed in Table 7.3.

Referring to Fig. 7.58 on p. 395, we construct the following table:

Material	Average normal anisotropy	Limited drawing ratio
Zinc alloys	0.4-0.6	1.8
Hot-rolled steel	0.8-1.0	2.3-2.4
Cold-rolled rimmed steel	1.0-1.4	2.3-2.5
Cold-rolled Al-killed steel	1.4-1.8	2.5-2.6
Aluminum alloys	0.6-.8	2.2-2.3
Copper and brass	0.6-0.9	2.3-2.4
Ti alloys (α)	3.0-5.0	2.9-3.0

7.76 For the same material and thickness as in Problem 7.66, estimate the force required for deep drawing with a blank of diameter 10 in. and a punch of diameter 9 in.

Note that $D_p = 9$ in., $D_o = 10$ in., $t_0 = 0.125$ in., and UTS = 125,000 psi. Therefore, Eq. (7.22) on p. 395 yields

$$\begin{aligned} F_{\max} &= \pi D_p t_o (\text{UTS})\left(\frac{D_o}{D_p} - 0.7\right) \\ &= \pi(9)(0.125)(125,000)\left(\frac{10}{9} - 0.7\right) \\ &= 181,000 \text{ lb} \end{aligned}$$

or $F_{\max} = 90$ tons.

7.77 A cup is being drawn from a sheet metal that has a normal anisotropy of 3. Estimate the maximum ratio of cup height to cup diameter that can successfully be drawn in a single draw. Assume that the thickness of the sheet throughout the cup remains the same as the original blank thickness.

For an average normal anisotropy of 3, Fig. 7.56 on p. 392 gives a limited drawing ratio of 2.68. Assuming incompressibility, one can equate the volume of the sheet metal in a cup to the volume in the blank. Therefore,

$$\left(\frac{\pi}{4}D_o^2\right)T = \pi D_p h T + \left(\frac{\pi}{4}D_p^2\right)T$$

This equation can be simplified as

$$\frac{\pi}{4}\left(D_o^2 - D_p^2\right) = \pi D_p h$$

where h is the can wall height. Note that the right side of the equation includes a volume for the wall as well as the bottom of the can. Thus, since $D_o/D_p = 2.68$,

$$\frac{\pi}{4}\left[(2.68D_p)^2 - D_p^2\right] = \pi D_p h$$

or

$$\frac{h}{D_p} = \frac{2.68^2 - 1}{4} = 1.55$$

7.78 Obtain an expression for the curve shown in Fig. 7.56 in terms of the LDR and the average normal anisotropy, $\bar{R}$ (*Hint:* See Fig. 2.5b).

Referring to Fig. 7.56 on p. 392, note that this is a log-log plot with a slope that is measured

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to be 8°. Therefore the exponent of the power curve is $\tan 8° = 0.14$. Furthermore, it can be seen that, for $\bar{R} = 1.0$, we have LDR=2.3. Therefore, the expression for the LDR as a function of the average strain ratio $\bar{R}$ is given by

$$\text{LDR} = 2.3\bar{R}^{0.14}$$

7.79 A steel sheet has R values of 1.0, 1.5, and 2.0 for the 0°, 45° and 90° directions to rolling, respectively. If a round blank is 150 mm in diameter, estimate the smallest cup diameter to which it can be drawn in one draw.

Substituting these values into Eq. (7.20) on p. 391 , we have

$$\bar{R} = \frac{1.0 + 2(1.5) + 2.0}{4} = 1.5$$

The limiting-drawing ratio can be obtained from Fig. 7.56 on p. 392, or it can be obtained from the expression given in the solution to Problem 7.78 as

$$\text{LDR} = 2.3\bar{R}^{0.14} = 2.43$$

Thus, the smallest diameter to which this material can be drawn is $150/2.43 = 61.7$ mm.

7.80 In Problem 7.79, explain whether ears will form and, if so, why.

Equation (7.21) on p. 392 yields

$$\begin{aligned}\Delta R &= \frac{R_0 - 2R_{45} + R_{90}}{2} \\ &= \frac{1.0 - 2(1.5) + 2.0}{2} = 0\end{aligned}$$

Since $\Delta R = 0$, no ears will form.

7.81 A 1-mm-thick isotropic sheet metal is inscribed with a circle 4 mm in diameter. The sheet is then stretched uniaxially by 25%. Calculate (a) the final dimensions of the circle and (b) the thickness of the sheet at this location.

Referring to Fig. 7.63b on p. 399 and noting that this is a case of uniaxial stretching, the circle will acquire the shape of an ellipse with a positive major strain and negative minor strain (due to the Poisson effect). The major axis of the ellipse will have undergone an engineering strain of (1.25-1)/1=0.25, and will thus have the dimension (4)(1+0.25)=5 mm. Because we have plastic deformation and hence the Poisson's ratio is $\nu = 0.5$, the minor engineering strain is -0.25/2=-0.125; see also the simple-tension line with a negative slope in Fig. 7.63a on p. 399. Thus, the minor axis will have the dimension

$$\frac{x - 4 \text{ mm}}{4 \text{ mm}} = -0.125$$

or $x = 3.5$ mm. Since the metal is isotropic, its final thickness will be

$$\frac{t - 1 \text{ mm}}{1 \text{ mm}} = 0 - 0.125$$

or $t = 0.875$ mm. The area of the ellipse will be

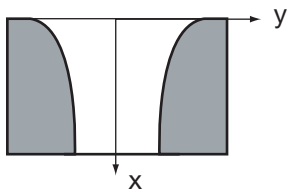
$$A = \pi \left(\frac{5 \text{ mm}}{2}\right)\left(\frac{3.5 \text{ mm}}{2}\right) = 13.7 \text{ mm}^2$$

The volume of the original circle is

$$V = \frac{\pi}{4}(4 \text{ mm})^2 (1 \text{ mm}) = 12.6 \text{ mm}^3$$

7.82 Conduct a literature search and obtain the equation for a tractrix curve, as used in Fig. 7.61.

The coordinate system is shown in the accompanying figure.



The equation for the tractrix curve is

$$\begin{aligned}x &= a \ln\left(\frac{a + \sqrt{a^2 - y^2}}{y}\right) - \sqrt{a^2 - y^2} \\ &= a \cosh^{-1}\left(\frac{a}{y}\right) - \sqrt{a^2 - y^2}\end{aligned}$$

where x is the position along the direction of punch travel, and y is the radial distance of the surface from the centerline.

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7.83 In Example 7.4, assume that the stretching is done by two equal forces F, each at 6 in. from the ends of the workpiece. (a) Calculate the magnitude of this force for $\alpha = 10°$. (b) If we want the stretching to be done up to $\alpha_{\max} = 50°$ without necking, what should be the minimum value of n of the material?

(1) Refer to Fig. 7.31 on p. 373 and note the following: (a) For two forces F at 6 in. from each end, the dimensions of the edge portions at $\alpha = 10°$ will be $6/\cos 10° = 6.09$ in. The total deformed length will thus be

$$L_f = 6.09 + 3.00 + 6.09 = 15.18 \text{ in.}$$

With a the true strain of

$$\epsilon = \ln\left(\frac{15.18}{15}\right) = 0.0119$$

and true stress of

$$\sigma = K\epsilon^n = (100,000)(0.0119)^{0.3} = 26,460 \text{ psi}$$

From volume constancy we can determine the stretched cross-sectional area,

$$A_f = \frac{A_o L_o}{L_f} = \frac{(0.05 \text{ in}^2)(15 \text{ in.})}{15.18} = 0.0494 \text{ in}^2$$

Consequently, the tensile force, which is uniform throughout the stretched part, is

$$F_t = (26,460 \text{ psi})(0.0495 \text{ in}^2) = 1310 \text{ lb}$$

The force F will be the vertical component of the tensile force in the stretched member (noting that the middle horizontal 3-in. portion does not have a vertical component). Therefore

$$F = \frac{1310 \text{ lb}}{\tan 10°} = 7430 \text{ lb}$$

(2) For $\alpha = 50°$, we have the total length of the stretched part as

$$L_f = 2\left(\frac{6 \text{ in.}}{\cos 50°}\right) + 3.00 \text{ in.} = 21.67 \text{ in.}$$

Hence the true strain will be

$$\epsilon = \ln\left(\frac{21.67}{15}\right) = 0.368$$

The necking strain should be equal to the strain-hardening exponent, or $n = 0.368$. Typical values of n are given in Table 2.3 on p. 37. Thus, 304 annealed stainless steel, phosphor bronze, or 70-30 annealed brass would be suitable metals for this application, as $n > 0.368$ for these materials.

7.84 Derive Eq. (7.5).

Referring to Fig. 7.15 on p. 360 and letting the bend-allowance length (i.e., length of the neutral axis) be l_o, we note that

$$l_o = \left(R + \frac{T}{2}\right)\alpha$$

and the length of the outer fiber is

$$l_f = (R + T)\alpha$$

where the angle α is in radians. The engineering strain for the outer fiber is

$$e_o = \frac{l_f - l_o}{l_o} = \frac{l_f}{l_o} - 1$$

Substituting the values of l_f and l_o, we obtain

$$e_o = \frac{1}{\left(\frac{2R}{T}\right) + 1}$$

7.85 Estimate the maximum power in shear spinning a 0.5-in. thick annealed 304 stainless-steel plate that has a diameter of 12 in. on a conical mandrel of $\alpha = 30°$. The mandrel rotates at 100 rpm and the feed is $f = 0.1$ in./rev.

Referring to Fig. 7.36b on p. 377 we note that, in this problem, $t_o = 0.5$ in., $\alpha = 30°$, $N = 100$ rpm, $f = 0.1$ in./rev., and, from Table 2.3 on p. 37, for this material $K = (1275)(145) = 185{,}000$ psi and $n = 0.45$. The power required in the operation is a function of the tangential force F_t, given by Eq. (7.13) as

$$F_t = ut_o f \sin\alpha$$

In order to determine u, we need to know the strain involved. This is calculated from Eq. (7.14) for the distortion-energy criterion as

$$\epsilon = \frac{\cot\alpha}{\sqrt{3}} = \frac{\cot 30°}{\sqrt{3}} = 1.0$$

and thus, from Eq. (2.60),

$$u = \frac{K\epsilon^{n+1}}{n+1} = \frac{(185,000)(1)^{1.45}}{1.45}$$

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or $u = 127,000$ in-lb/in^3. Therefore,

$$F_t = (127,000)(0.5)(0.1)(\sin 30^\circ) = 3190 \text{ lb}$$

and the maximum torque required is at the 15 in. diameter, hence

$$T = (3190 \text{ lb})\left(\frac{12 \text{ in.}}{2}\right) = 19,140 \text{ in-lb}$$

or $T = 1590$ ft-lb. Thus the maximum power required is

$$\begin{aligned} P_{\max} &= T\omega \\ &= (19,140 \text{ in.-lb})(100 \text{ rev/min}) \\ &\quad \times (2\pi \text{ rad/rev}) \\ &= 12.03 \times 10^6 \text{ in-lb/min} \end{aligned}$$

or 30.3 hp. As stated in the text, because of redundant work and friction, the actual power may be as much as 50% higher, or up to 45 hp.

7.86 Obtain an aluminum beverage can and cut it in half lengthwise with a pair of tin snips. Using a micrometer, measure the thickness of the bottom of the can and of the wall. Estimate (a) the thickness reductions in ironing of the wall and (b) the original blank diameter.

Note that results will vary depending on the specific can design. In one example, results for a can diameter of 2.6 in. and a height of 5 in., the sidewall is 0.003 in. and the bottom is 0.0120 in. thick. The wall thickness reduction in ironing is then

$$\begin{aligned} \%\text{red} &= \frac{t_o - t_f}{t_o} \times 100\% \\ &= \frac{0.0120 - 0.003}{0.012} \times 100\% \\ &= 75\% \end{aligned}$$

The initial blank diameter can be obtained by volume constancy. The volume of the can material after deep drawing and ironing is

$$\begin{aligned} V_f &= \frac{\pi d_c^2}{4} t_o + \pi d t_w h \\ &= \frac{\pi (2.5)^2}{4}(0.012) + \pi(2.5)(0.003)(5) \\ &= 0.1767 \text{ in}^3 \end{aligned}$$

Since the initial blank has a thickness equal to the final can bottom (i.e., 0.0120 in.) and a diameter d, the volume is

$$0.1767 \text{ in}^3 = \frac{\pi d^2}{4} t_o = \frac{\pi d^2}{4}(0.012 \text{ in})$$

or $d = 4.33$ in.

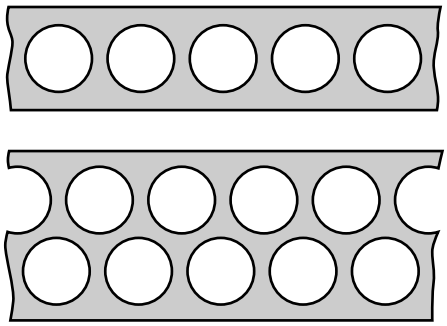
7.87 What is the force required to punch a square hole, 150 mm on each side, from a 1-mm-thick 5052-O aluminum sheet, using flat dies? What would be your answer if beveled dies were used instead?

This problem is very similar to Problem 7.71. The punch force is given by Eq. (7.4) on p. 353. Table 3.7 on p. 116 gives the UTS of 5052-O aluminum as UTS=190 MPa. The sheet thickness is $t = 1.0$ mm $= 0.001$ m, and $L = (4)(150mm) = 600$ mm $= 0.60$ m. Therefore, from Eq. (7.4) on p. 353,

$$\begin{aligned} F_{\max} &= 0.7(\text{UTS})(t)(L) \\ &= 0.7(190 \text{ MPa})(0.001 \text{ m})(0.60 \text{ m}) \\ &= 79,800 \text{ N} = 79.8 \text{ kN} \end{aligned}$$

If the dies are beveled, the punch force could be much lower than calculated here. For a single bevel with contact along one face, the force would be calculated as 19,950 N, but for double-beveled shears, the force could be essentially zero.

7.88 Estimate the percent scrap in producing round blanks if the clearance between blanks is one tenth of the radius of the blank. Consider single and multiple-row blanking, as shown in the accompanying figure.



(a) A repeating unit cell for the part the upper illustration is shown below.

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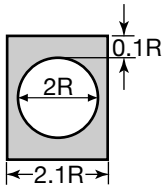


The area of the unit cell is $A = (2.2R)(2.1R) = 4.62R^2$. The area of the circle is $3.14R^2$. Therefore, the scrap is

$$\text{scrap} = \frac{4.62R^2 - 3.14R^2}{4.62R^2} \times 100 = 32\%$$

(b) Using the same approach, it can be shown that for the lower illustration the scrap is 26%.

7.89 Plot the final bend radius as a function of initial bend radius in bending for (a) 5052-O aluminum; (b) 5052-H34 Aluminum; (c) C24000 brass and (d) AISI 304 stainless steel sheet.

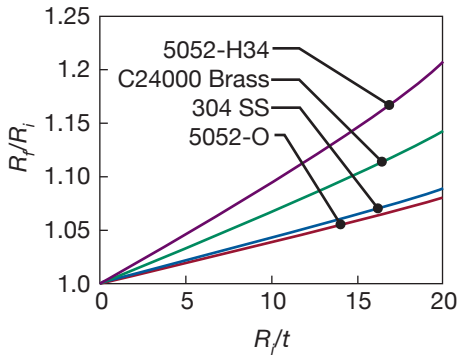
The final bend radius can be determined from Eq. (7.10) on p. 364 . Solving this equation for R_f gives:

$$R_f = \frac{R_i}{4\left(\frac{R_iY}{Et}\right)^3 - 3\left(\frac{R_iY}{Et}\right) + 1}$$

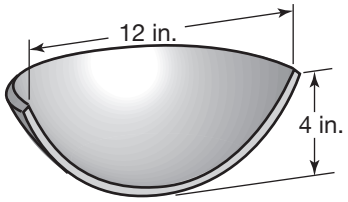
Using Tables 2.1 on p. 32, 3.4, 3.7, and 3.10, the following data is compiled:

Material	Y (MPa)	E (GPa)
5052-O Al	90	73
5052-H34	210	73
C24000 Brass	265	127
AISI 304 SS	265	195

where mean values of Y and E have been assigned. From this data, the following plot is obtained. Note that the axes have been defined so that the value of t is not required.



7.90 The accompanying figure shows a parabolic profile that will define the mandrel shape in a spinning operation. Determine the equation of the parabolic surface. If a spun part is to be produced from a 10-mm thick blank, determine the minimum blank diameter required. Assume that the diameter of the profile is 6 in. at a distance of 3 in. from the open end.



Since the shape is parabolic, it is given by

$$y = ax^2 + bx + c$$

where the following boundary conditions can be used to evaluate constant coefficients a, b, and c:

(a) at $x = 0$, $\frac{dy}{dx} = 0$.
(b) at $x = 3$ in., $y = 1$ in.
(c) at $x = 6$ in., $y = 4$ in.

The first boundary condition gives:

$$\frac{dy}{dx} = 2ax + b$$

Therefore,

$$0 = 2a(0) + b$$

or $b = 0$. Similarly, the second and third boundary conditions result in two simultaneous algebraic equations:

$$36a + c = 4$$

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and

$$9a + c = 1$$

Thus, $a = \frac{1}{9}$ and $c = 0$, so that the equation for the mandrel surface is

$$y = \frac{x^2}{9}$$

If the part is conventionally spun, the surface area of the mandrel has to be calculated. The surface area is given by

$$A = \int_0^6 2\pi R\, ds$$

where $R = x$ and

$$ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx = \sqrt{1 + \left(\frac{2}{9}x\right)^2}\, dx$$

Therefore, the area is given by

$$\begin{aligned} A &= \int_0^6 2\pi x \sqrt{1 + \left(\frac{2}{9}x\right)^2}\, dx \\ &= \int_0^6 2\pi x \sqrt{1 + \frac{4}{81}x^2}\, dx \end{aligned}$$

To solve this integral, substitute a new variable, $u = 1 + \frac{4}{81}x^2$, so that

$$du = \frac{8}{81}x\, dx$$

and so that the new integration limits are from $u = 1$ to $u = \frac{225}{81}$. Therefore, the integral becomes

$$\begin{aligned} A &= \int_1^{225/81} 2\pi \frac{81}{8}\sqrt{u}\, du \\ &= \frac{81\pi}{4}\left(\frac{2}{3}u^{3/2}\right)_1^{225/81} \\ &= 154 \text{ in}^2 \end{aligned}$$

For a disk of the same surface area and thickness,

$$A_{\text{blank}} = \frac{\pi}{4}d^2 = 154 \text{ in}^2$$

or $d = 14$ in.

7.91 For the mandrel needed in Problem 7.90, plot the sheet-metal thickness as a function of radius if the part is to be produced by shear spinning. Is this process feasible? Explain.

As was determined in Problem 7.90, the equation of the surface is

$$y = \frac{x^2}{9}$$

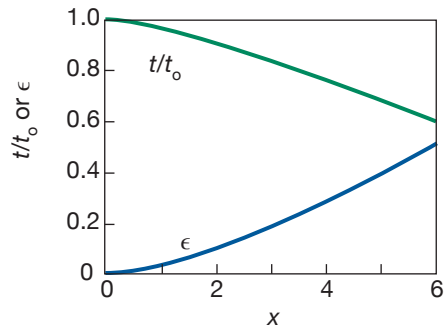
The sheet-metal thickness in shear spinning is given by Eq. (7.12) on p. 377 as

$$t = t_o \sin\alpha$$

where α is given by (see Fig. 7.36 on p. 377)

$$\alpha = 90^\circ - \tan^{-1}\left(\frac{dy}{dx}\right) = 90^\circ - \tan^{-1}\left(\frac{2}{9}x\right)$$

This results in the following plot of sheet thickness:



Note that at the edge of the shape, $t/t_o = 0.6$, corresponding to a strain of $\epsilon = \ln 0.6 = -0.51$. This strain is achievable for many materials, so that the process is feasible.

7.92 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare five quantitative problems and five qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

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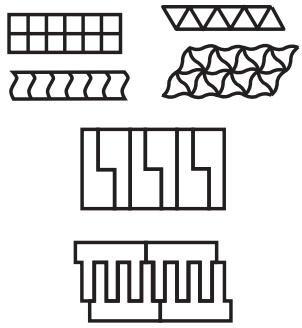
Design

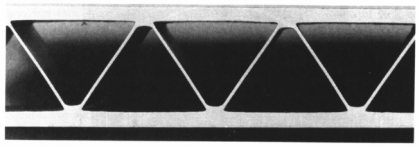
7.93 Consider several shapes (such as oval, triangle, *L*-shape, etc.) to be blanked from a large flat sheet by laser-beam cutting, and sketch a nesting layout to minimize scrap.

Several answers are possible for this open-ended problem. The following examples were obtained from Altan, T., ed., *Metal Forming Handbook*, Springer, 1998:

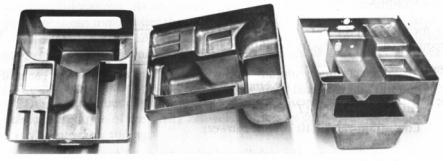


7.94 Give several structural applications in which diffusion bonding and superplastic forming are used jointly.

By the student. The applications for superplastic forming are mainly in the aerospace industry. Some structural-frame members, which normally are placed behind aluminum sheet and are not visible, are made by superplastic forming. Two examples below are from Hosford and Cadell, *Metal Forming*, 2nd ed., pp. 85-86.



Aircraft wing panel, produced through internal pressurization. See also Fig. 7.46 on p. 384.



Sheet-metal parts.

7.95 On the basis of experiments, it has been suggested that concrete, either plain or reinforced, can be a suitable material for dies in sheet-metal forming operations. Describe your thoughts regarding this suggestion, considering die geometry and any other factors that may be relevant.

By the student. Concrete has been used in explosive forming for large dome-shaped parts intended, for example, as nose cones for intercontinental ballistic missiles. However, the use of concrete as a die material is rare. The more serious limitations are in the ability of consistently producing smooth surfaces and acceptable tolerances, and the tendency of concrete to fracture at stress risers.

7.96 Metal cans are of either the two-piece variety (in which the bottom and sides are integral) or the three-piece variety (in which the sides, the bottom, and the top are each separate pieces). For a three-piece can, should the seam be (a) in the rolling direction, (b) normal to the rolling direction, or (c) oblique to the rolling direction of the sheet? Explain your answer, using equations from solid mechanics.

The main concern for a beverage container is that the can wall should not fail under stresses due to internal pressurization. (Internal pressurization routinely occurs with carbonated beverages because of jarring, dropping, and rough handling and can also be caused by temperature changes.) The hoop stress and the axial stress are given, respectively, by

$$\sigma_h = \frac{pr}{t}$$

$$\sigma_a = \frac{1}{2}\sigma_h = \frac{pr}{2t}$$

where p is the internal pressure, r is the can radius, and t is the sheet thickness. These are principal stresses; the third principal stress is in the radial direction and is so small that it can be neglected. Note that the maximum stress is in the hoop direction, so the seam should be perpendicular to the rolling direction.

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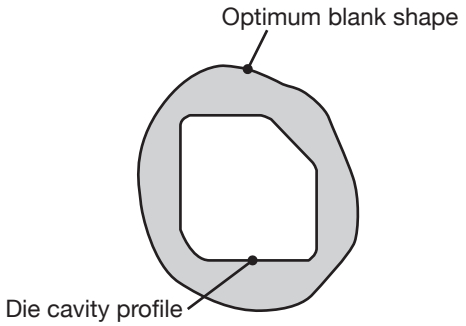
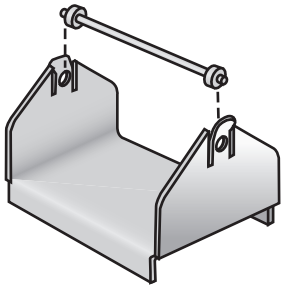
7.97 Investigate methods for determining optimum shapes of blanks for deep-drawing operations. Sketch the optimally shaped blanks for drawing rectangular cups, and optimize their layout on a large sheet of metal.

This is a topic that continues to receive considerable attention. Finite-element simulations, as well as other techniques such as slip-line field theory, have been used. An example of an optimum blank for a typical oil-pan cup is sketched below.



7.98 The design shown in the accompanying illustration is proposed for a metal tray, the main body of which is made from cold-rolled sheet steel. Noting its features and that the sheet is bent in two different directions, comment on relevant manufacturing considerations. Include factors such as anisotropy of the cold-rolled sheet, its surface texture, the bend directions, the nature of the sheared edges, and the method by which the handle is snapped in for assembly.



By the student. Several observations can be made. Note that a relief notch design, as shown in Fig. 7.68 on p. 405 has been used. It is a valuable experiment to have the students cut the blank from paper and verify that the tray is produced by bending only because of this notch. As such, the important factors are bendability, and scoring such as shown in Fig. 7.71 on p. 406, and avoiding wrinkling such as discussed in Fig. 7.69 on p. 405.

7.99 Design a box that will contain a 4 in. × 6 in. × 3 in. volume. The box should be produced from two pieces of sheet metal and require no tools or fasteners for assembly.

This is an open-ended problem with a wide variety of answers. Students should consider the blank shape, whether the box will be deep-drawn or produced by bending operations (see Fig. 7.68), the method of attaching the parts (integral snap-fasteners, folded flaps or loose-fit), and the dimensions of the two halves are all variables. It can be beneficial to have the students make prototypes of their designs from cardboard.

7.100 Repeat Problem 7.99, but the box is to be made from a single piece of sheet metal.

This is an open-ended problem; see the suggestions in Problem 7.99. Also, it is sometimes helpful to assign both of these problems, or to assign each to one-half of a class.

7.101 In opening a can using an electric can opener, you will note that the lid often develops a scalloped periphery. (a) Explain why scalloping occurs. (b) What design changes for the can opener would you recommend in order to minimize or eliminate, if possible, this scalloping effect? (c) Since lids typically are recycled or discarded, do you think it is necessary or worthwhile to make such design changes? Explain.

By the student. The scalloped periphery is due to the fracture surface moving ahead of the shears periodically, combined with the loading applied by the two cutting wheels. There are several potential design changes, including changing the plane of shearing, increasing the speed of shearing, increasing the stiffness of the support structure, or using more wheels. Scallops on the cans are not normally objectionable, so there has not been a real need to make openers that avoid this feature.

7.102 A recent trend in sheet-metal forming is to provide a specially-textured surface finish that de-

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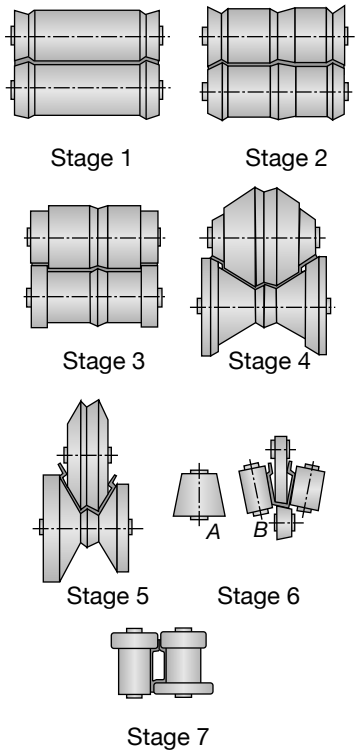
velops small pockets to aid lubricant entrainment. Perform a literature search on this technology, and prepare a brief technical paper on this topic.

This is a valuable assignment, as it encourages the student to conduct a literature review. This is a topic where significant research has been done, and a number of surface textures are available. A good starting point is to obtain the following paper:

Hector, L.G., and Sheu, S., "Focused energy beam work roll surface texturing science and technology," *J. Mat. Proc. & Mfg. Sci.*, v. 2, 1993, pp. 63-117.



7.103 Lay out a roll-forming line to produce any three cross sections from Fig. 7.27b.

By the student. An example is the following layout for the structural member in a steel door frame:

7.104 Obtain a few pieces of cardboard and carefully cut the profiles to produce bends as shown in Fig. 7.68. Demonstrate that the designs labeled as "best" are actually the best designs. Comment on the difference in strain states between the designs.

By the student. This is a good project that demonstrates how the designs in Fig. 7.68 on p. 405 significantly affect the magnitude and type of strains that are applied. It clearly shows that the best design involves no stretching, but only bending, of the sheet metal.

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Chapter 8

Material-Removal Processes: Cutting

Questions

8.1 Explain why the cutting force, F_c, increases with increasing depth of cut and decreasing rake angle.

(a) Increasing the depth of cut means more material being removed per unit time. Thus, all other parameters remaining constant, the cutting force has to increase linearly because the energy requirement increases linearly.

(b) As the rake angle decreases, the shear angle decreases and hence the shear strain increases. Therefore, the energy per unit volume of material removed increases, thus the cutting force has to increase. Note that the rake angle also has an effect on the frictional energy (see Table 8.1 on p. 430).

8.2 What are the effects of performing a cutting operation with a dull tool tip? A very sharp tip?

There are several effects of a dull tool. Note that a dull tool is one having an increased tip radius (see Fig. 8.28 on p. 449). As the tip radius increases (i.e., as the tool dulls), the cutting force increases due to the fact that the effective rake angle is now decreased. In fact, shallow depths of cut may not be possible. Another effect is the possibility for surface residual stresses, tearing, and cracking of the machined surface, due to severe surface deformation and the heat generated by the dull tool tip rubbing against this surface. Dull tools also increase the tendency for BUE formation, which leads to poor surface finish.

8.3 Describe the trends that you observe in Tables 8.1 and 8.2.

By the student. A review of Tables 8.1 and 8.2 on pp. 430-431 indicates certain trends that are to be expected, including:

(a) As the rake angle decreases, the shear strain and hence the specific energy increase.

(b) Cutting force also increases with decreasing rake angle;

(c) Shear plane angle decreases with increasing rake angle.

8.4 To what factors would you attribute the large difference in the specific energies within each group of materials shown in Table 8.3?

The differences in specific energies seen in Table 8.3 on p. 435, whether among different materials or within types of materials, can basically be attributed to differences in the mechanical and physical properties of these materials, which affect the cutting operation. For example, as strength increases, so does the total specific energy. Differences in tool-chip interface friction characteristics would also play a significant role. Physical properties, such as thermal

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conductivity and specific heat, both of which increase cutting temperatures as they decrease, could be responsible for such differences. These points are supported when one closely examines this table and observes that the ranges for materials such as steels, refractory alloys, and high-temperature alloys are large, in agreement with our knowledge of the great variety of these classes of materials.

8.5 Describe the effects of cutting fluids on chip formation. Explain why and how they influence the cutting operation.

By the student. In addition to the effects discussed in Section 8.7 starting on p. 464, cutting fluids influence friction at the tool-chip interface, thus affecting the shear angle and chip thickness. These, in turn, can influence the type of chip produced. Also, note that with effective cutting fluids the built-up edge can be reduced or eliminated.

8.6 Under what conditions would you discourage the use of cutting fluids? Explain.

By the student. The use of cutting fluids could be discouraged under the following conditions:

(a) If the cutting fluid has any adverse effects on the workpiece and/or machine-tool components, or on the overall cutting operation.

(b) In interrupted cutting operations, such as milling, the cutting fluid will, by its cooling action, subject the tool to large fluctuations in temperature, possibly causing thermal fatigue of the tool, particularly in ceramics.

8.7 Give reasons that pure aluminum and copper are generally rated as easy to machine.

There are several reasons that aluminum and copper are easy to machine. First, they are relatively soft, hence cutting forces and energy are low compared to many other materials. Furthermore, they are good thermal conductors. Also, they are ductile and can withstand the strains in cutting and still develop continuous chips. These materials do not generally form a built-up edge, depending on cutting parameters.

8.8 Can you offer an explanation as to why the maximum temperature in cutting is located at about the middle of the tool-chip interface? (*Hint:* Note that there are two principal sources of heat: the shear plane and the tool-chip interface.)

It is reasonable that the maximum temperature in orthogonal cutting is located at about the middle of the tool-chip interface. The chip reaches high temperatures in the primary shear zone; the temperature would decrease from then on as the chip climbs up the rake face of the tool. If no frictional heat was involved, we would thus expect the highest temperature to occur at the shear plane. However, recall that friction at the tool-chip interface also increases the temperature. After the chip is formed it slides up the rake face and temperature begins to build up. Consequently, the temperature due only to frictional heating would be highest at the end of the tool-chip contact. These two opposing effects are additive, and as a result the temperature is highest somewhere in between the tip of the tool and the end of contact zone.

8.9 State whether or not the following statements are true for orthogonal cutting, explaining your reasons: (a) For the same shear angle, there are two rake angles that give the same cutting ratio. (b) For the same depth of cut and rake angle, the type of cutting fluid used has no influence on chip thickness. (c) If the cutting speed, shear angle, and rake angle are known, the chip velocity can be calculated. (d) The chip becomes thinner as the rake angle increases. (e) The function of a chip breaker is to decrease the curvature of the chip.

(a) To show that for the same shear angle there are two rake angles and given the same cutting ratio, recall the definition of the cutting ratio as given by Eq. (8.1) on p. 420. Note that the numerator is constant and that the cosine of a positive and negative angle for the denominator has the same value. Thus, there are two rake angles that give the same r, namely a rake angle, α, greater than the shear angle, ϕ, and a rake angle smaller than the shear angle by the same amount.

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(b) Incorrect, because the cutting fluid will influence friction, hence the shear angle and, consequently, the chip thickness.

(c) Correct, because if the cutting speed, V, shear angle, ϕ, and rake angle, α, are all known, the velocity of the chip up the face of the tool (V_o) can be calculated. This is done simply by using Eq. (8.5).

(d) Correct, as can be seen in Table 8.1 on p. 430.

(e) Incorrect; its function is to decrease the radius of curvature, that is, to increase curvature.

8.10 It has been stated that it is generally undesirable to allow temperatures to rise excessively in machining operations. Explain why.

By the student. This is an open-ended problem with a large number of acceptable answers. The consequences of allowing temperatures to rise to high levels in cutting include:

(a) Tool wear will be accelerated due to high temperatures.

(b) High temperatures will cause dimensional changes in the workpiece, thus reducing dimensional accuracy.

(c) Excessively high temperatures in the cutting zone may induce metallurgical changes and cause thermal damage to the machined surface, thus affecting surface integrity.

8.11 Explain the reasons that the same tool life may be obtained at two different cutting speeds.

Tool life in this case refers to flank wear. At low cutting speeds, the asperities at the tool-workpiece interface have more time to form a stronger junction, thus wear is likely to increase (see Section 4.4.2 starting on p. 144). Furthermore, at low speeds some microchipping of cutting tools have been observed (due possibly to the same reasons), thus contributing to tool wear. At high cutting speeds, on the other hand, temperature increases, thus increasing tool wear.

8.12 Inspect Table 8.6 and identify tool materials that would not be particularly suitable for interrupted cutting operations, such as milling. Explain your choices.

By the student. In interrupted cutting operations, it is desirable to have tools with high impact strength and toughness. From Table 8.6 on p. 454 the tool materials that have the best impact strength are high-speed steels, and, to a lesser extent, cast alloys and carbides. Note also that carbon steels and alloy steels also have high toughness. In addition, with interrupted cutting operations, the tool is constantly being subjected to thermal cycling. It is thus desirable to utilize materials with low coefficients of thermal expansion and high thermal conductivity to minimize thermal stresses in the tool (see pp. 107-108).

8.13 Explain the possible disadvantages of a machining operation if a discontinuous chip is produced.

By the student. The answer is given in Section 8.2.1. Note that:

(a) The forces will continuously vary, possibly leading to chatter and all of its drawbacks.

(b) Tool life will be reduced.

(c) Surface finish may be poor surface.

(d) Tolerances may not be acceptable.

8.14 It has been noted that tool life can be almost infinite at low cutting speeds. Would you then recommend that all machining be done at low speeds? Explain.

As can be seen in Fig. 8.21 on p. 441, tool life can be almost infinite at very low cutting speeds, but this reason alone would not always justify using low cutting speeds. Low cutting speeds will remove less material in a given time which could be economically undesirable. Lower cutting speeds often also lead to the formation of built-up edge and discontinuous chips. Also, as cutting speed decreases, friction increases and the shear angle decreases, thus generally causing the cutting force to increase.

8.15 Referring to Fig. 8.31, how would you explain the effect of cobalt content on the properties of carbides?

Recall that tungsten-carbide tools consist of tungsten-carbide particles bonded together in

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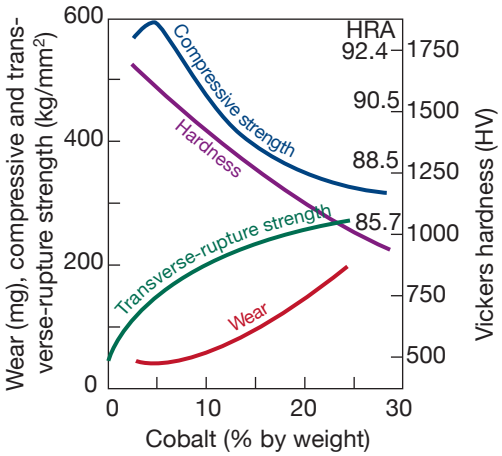
a cobalt matrix using powder-metallurgy techniques. Increasing the amount of cobalt will make the material behave in a more ductile manner, thus adversely affecting the strength, hardness, and wear resistance of the tungsten-carbide tools. The property which cobalt improves is toughness and transverse-rupture strength. The accompanying figure was taken from p. 502 of S. Kalpakjian, *Manufacturing Processes for Engineering Materials*, 3d ed., 1997.



8.16 Explain why studying the types of chips produced is important in understanding machining operations.

By the student. The study the types of chips produced is important because the type of chip significantly influences the surface finish produced as well as the overall cutting operation. For example, continuous chips are generally associated with good surface finish. Built-up-edge chips usually result in poor surface finish. Serrated chips and discontinuous chips may result in poor surface finish and dimensional accuracy, and possibly lead to chatter.

8.17 How would you expect the cutting force to vary for the case of serrated-chip formation? Explain.

By the student. One would expect the cutting force to vary under cutting conditions producing serrated chips. During the continuous-chip formation period, the cutting force would be relatively constant. As this continuous region becomes segmented, the cutting force would rapidly drop to some lower value, and then begin rising again, starting a new region of continuous chip. The whole process is repeated over and over again.

8.18 Wood is a highly anisotropic material; that is, it is orthotropic. Explain the effects of orthogonal cutting of wood at different angles to the grain direction on the types of chips produced.

When cutting a highly anisotropic material such as wood (orthotropic), the chip formation would depend on the direction of the cut with respect to the wood grain direction and the rake angle of the tool. The shear strength of wood is low (and tensile strength is high) in the grain direction, and high when perpendicular to the grain direction. Cutting wood along the grain direction would produce long continuous chips by virtue of a splitting action ahead of the tool. Thus, the chip is more like a shaving or veneer (and can become a polygonal in shape at large depths of cut, like cracking a toothpick at constant intervals along its length). Cutting across the grain would produce discontinuous chips; cutting along a direction where the shear plane is in the same direction as the grain of the wood can produce continuous chips, similar to those observed in metal cutting. These phenomena can be demonstrated with a wood plane and piece of pine (see, for example, Kalpakjian, *Mechanical Processing of Materials*, 1963, p. 315). These observations are also relevant to cutting single-crystal materials, which exhibit high anisotropy.

8.19 Describe the advantages of oblique cutting. Which machining proceses involve oblique cutting? Explain.

A major advantage of oblique cutting is that the chip moves off to the side of the cutting zone, thus out of the way of the working area (see Fig. 8.9 on p. 426). Thus it is better suited for cutting operations involving a cross feed as in turning. Note also that the effective rake angle is increased and the chip is thinner.

8.20 Explain why it is possible to remove more material between tool resharpenings by lowering the cutting speed.

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This situation can be visualized by referring to Fig. 8.21a on p. 441. Note that at any location on a particular curve, the product of cutting speed (ft/min) and tool life (min) is the distance (ft) the tool travels before it reached the end of its life (a specified wear land). The distance traveled is directly proportional to the volume of material removed. Note also in the figure that at very high speeds, tool life is virtually zero, so is the material removed. Conversely, at very low speeds, tool life is virtually infinite, thus the volume removed is almost infinite.

It is therefore apparent that more material can be removed by lowering the cutting speed. However, there are two important considerations:

(a) The economics of the machining process will be adversely affected if cutting speeds are low, as described in Section 8.15 and shown in Fig. 8.75 on p. 509.

(b) As stated in Section 8.3.1, tool-life curves can curve downward at low cutting speeds. Consequently, there would be a specific cutting speed where material removal between tool changes is a maximum.

8.21 Explain the significance of Eq. (8.8).

The main significance of Eq. (8.8) on p. 427 is that it determines an effective rake angle for oblique cutting (a process of more practical significance than orthogonal cutting), which can be related back to the simpler orthogonal cutting models for purposes of analysis.

8.22 How would you go about measuring the hot hardness of cutting tools? Explain any difficulties that may be involved.

Hot hardness refers to the hardness of the material at the elevated temperatures typical of the particular cutting operation (see Fig. 8.30 on p. 453). Once the temperature is known (which can be measured with thermocouples or can be estimated), the hardness of the material can be evaluated at this temperature. A simple method of doing so is by heating the tool material, then subjecting it to a hardness test while it is still hot.

8.23 Describe the reasons for making cutting tools with multiphase coatings of different materials. Describe the properties that the substrate for multiphase cutting tools should have for effective machining.

By the student; see Section 8.6.5. One can combine benefits from different materials. For example, the outermost layer can be the coating which is best from hardness or low frictional characteristics to minimize tool wear. The next layer can have the benefit of being thermally insulating, and a third layer may be of a material which bonds well to the tool. Using these multiple layers allows a synergistic result in that the limitations of one coating can be compensated for with another layer.

8.24 Explain the advantages and any limitations of inserts. Why were they developed?

With inserts, a number of new cutting edges are available on each tool, so that the insert merely needs to be indexed. Also, since inserts are clamped relatively easily, they allow for quick setups and tool changes. There are no significant limitations to inserts other than the fact that they require special toolholders, and that they should be clamped properly. Their recycling and proper disposal is also an important consideration.

8.25 Make a list of alloying elements in high-speed-steel cutting tools. Explain why they are used.

Typical alloying elements for high-speed steel are chromium, vanadium, tungsten, and cobalt (see Section 8.6.2). These elements serve to produce a material with higher strength, hardness, and wear resistance at elevated temperatures. (See also Section 3.10.3.)

8.26 What are the purposes of chamfers on cutting tools? Explain.

Chamfers serve to increase the strength of inserts by effectively increasing the included angle of the insert. This trend is shown in Fig. 8.34 on p. 458. The tendency of edge chipping is thus reduced.

8.27 Why does temperature have such an important effect on cutting-tool performance?

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Temperature has a large effect on the life of a cutting tool. (a) Materials become weaker and softer as they become hotter (see Fig. 8.30 on p. 453), hence their wear resistance is reduced. (b) Chemical reactivity generally increases with increasing temperature, thus increasing the wear rate. (c) The effectiveness of cutting fluids can be compromised at excessive temperatures. (d) Because of thermal expansion, workpiece tolerances will be adversely affected.

8.28 Ceramic and cermet cutting tools have certain advantages over carbide tools. Why, then, are carbide tools not replaced to a greater extent?

Ceramics are preferable to carbides in that they have a lower tendency to adhere to metals being cut, and have very high abrasion resistance and hot hardness. However, ceramics are sensitive to defects and are generally brittle, and thus can fail prematurely. Carbides are much tougher than ceramics, and are therefore much more likely to perform as expected even when conditions such as chatter occur. (See also Section 11.8.)

8.29 Why are chemical stability and inertness important in cutting tools?

Chemical stability and inertness are important for cutting tools to maintain low friction and wear (see also Section 4.4). A major cause of friction is the shear stress required to break the microwelds in the contact area between the two materials. If the tool material is inert, the microwelds are less likely to occur with the workpiece material, and friction and wear will thus be reduced.

8.30 What precautions would you take in machining with brittle tool materials, especially ceramics? Explain.

With brittle tool materials, we first want to prevent chipping, such as by using negative rake angles and reduce vibration and chatter. Also, brittleness of ceramic tools applies to thermal gradients, as well as to strains. To prevent tool failures due to thermal gradients, a steady supply of cutting fluid should be applied, as well as selecting tougher tool materials.

8.31 Why do cutting fluids have different effects at different cutting speeds? Is the control of cutting-fluid temperature important? Explain.

A cutting fluid has been shown to be drawn into the asperities between the tool and chip through capillary action. At low cutting speeds, the fluid has longer time to penetrate more of the interface and will thus be effective in reducing friction acting as a lubricant. At higher cutting speeds, the fluid will have less time to penetrate the asperities; therefore, it will be less effective at higher speeds. Furthermore, cutting fluids whose effectiveness depends on their chemical reactivity with surfaces, will have less time to react and to develop low-shear-strength films. At higher cutting speeds, temperatures increase significantly and hence cutting fluids should have a cooling capacity as a major attribute.

8.32 Which of the two materials, diamond or cubic boron nitride, is more suitable for machining steels? Why?

Of the two choices, cubic boron nitride is more suitable for cutting steel than diamond tools. This is because cBN, unlike diamond, is chemically inert to iron at high temperatures, thus tool life is better.

8.33 List and explain the considerations involved in determining whether a cutting tool should be reconditioned, recycled, or discarded after use.

By the student. This is largely a matter of economics. Reconditioning requires skilled labor, grinders, and possibly recoating equipment. Other considerations are the cost of new tools and possible recycling of tool materials, since many contain expensive materials of strategic importance such as tungsten and cobalt.

8.34 List the parameters that influence the temperature in machining, and explain why and how they do so.

By the student. An inspection of Eq. (8.29) on p. 438 indicates that temperature increases with strength, cutting speed, and depth of cut. This is to be expected because:

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(a) strength indicates energy dissipation, thus higher heat content,

(b) the higher the cutting speed, the less time for heat to be dissipated, and

(c) the greater the depth of cut, the smaller the surface area-to-thickness ratio of the chip, thus less heat dissipation. In the denominator of this equation are specific heat and thermal conductivity, both of which influence heat conduction and dissipation.

8.35 List and explain the factors that contribute to poor surface finish in machining operations.

By the student. Recall, for example, in turning or milling, as the feed per tooth increases or as the tool radius decreases, the roughness increases. Other factors that contribute to poor surface finish are built-up edge, tool chipping or fracture, and chatter. Each of these factors can adversely affect any of the processes described in the chapter. See also Section 8.4.

8.36 Explain the functions of the different angles on a single-point lathe cutting tool. How does the chip thickness vary as the side cutting-edge angle is increased? Explain.

These are described in Section 8.8.1 and can also be found in various handbooks on machining. As the side cutting-edge angle is increased, the chip becomes thinner because it becomes wider (see Fig. 8.41 on p. 470).

8.37 It will be noted that the helix angle for drills is different for different groups of workpiece materials. Why?

The reasons are to control chip flow through the flutes and to avoid excessive temperature rise, which would adversely affect the drilling operation. These considerations are especially important in drilling thermoplastics, which tend to become gummy. The student is encouraged to survey the literature and give a comprehensive answer.

8.38 A turning operation is being carried out on a long, round bar at a constant depth of cut. Explain what differences, if any, there may be in the machined diameter from one end of the bar to the other. Give reasons for any changes that may occur.

The workpiece diameter can vary from one end of the bar to the other because the cutting tool is expected to wear, depending on workpiece materials, processing parameters, and the effectiveness of the cutting fluid. It can be seen that with excessive flank wear, the diameter of the bar will increase towards the end of the cut. Temperature variations will also affect workpiece diameter.

8.39 Describe the relative characteristics of climb milling and up milling and their importance in machining operations.

By the student. The answer can be found in Section 8.10.1. Basically, in up (conventional) milling, the maximum chip thickness is at the exit of tooth engagement and, thus, contamination and scale on the workpiece surface does not have a significant effect on tool life. Climb milling has been found to have a lower tendency to chatter, and the downward component of the cutting force holds the workpiece in place. Note, however, that workpiece surface conditions can affect tool wear.

8.40 In Fig. 8.64a, high-speed-steel cutting teeth are welded to a steel blade. Would you recommend that the whole blade be made of high-speed steel? Explain your reasons.

It is desirable to have a hard, abrasion-resistant tool material (such as HSS or carbide) on the cutting surface and a tough, thermally conductive material in the bulk of the blade. This is an economical method of producing high-quality steel saw blades. To make the whole blade from HSS would be expensive and unnecessary.

8.41 Describe the adverse effects of vibrations and chatter in machining.

By the student. The adverse effects of chatter are discussed in Section 8.11 and are summarized briefly below:

- Poor surface finish, as shown in the right central region of Fig. 8.72 on p. 501.
- Loss of dimensional accuracy of the workpiece.

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- Premature tool wear, chipping, and failure, a critical consideration with brittle tool materials, such as ceramics, some carbides, and diamond.
- Possible damage to the machine-tool components from excessive vibration and chatter.
- Objectionable noise, particularly if it is of high frequency, such as the squeal heard when turning brass on a lathe with a less rigid setup.

8.42 Make a list of components of machine tools that could be made of ceramics, and explain why ceramics would be a suitable material for these components.

By the student. Typical components would be members that reciprocate at high speeds or members that move at high speeds and are brought to rest in a short time (inertia effects). Bearing components are also suitable applications by virtue of the hardness, resistance, and low inertial forces with ceramics (due to their lower density).

8.43 In Fig. 8.12, why do the thrust forces start at a finite value when the feed is zero? Explain.

The reason is likely due to the fact that the tool has a finite tip radius (see Fig. 8.28 on p. 449), and that some rubbing along the machined surface takes place regardless of the magnitude of feed.

8.44 Is the temperature rise in cutting related to the hardness of the workpiece material? Explain.

Because hardness and strength are related (see Section 2.6.8), the hardness of the workpiece material would influence the temperature rise in cutting by requiring higher energy.

8.45 Describe the effects of tool wear on the workpiece and on the overall machining operation.

By the student. Tool wear can adversely affect temperature rise of the workpiece, cause excessive rubbing of the machined surface resulting in burnishing, and induce residual stresses, surface damage, and cracking. Also, the machining operation is influenced by increased forces and temperatures, loss of dimensional control, and possibly causing vibration and chatter as well.

8.46 Explain whether or not it is desirable to have a high or low (a) n value and (b) C value in the Taylor tool-life equation.

As we can see in Fig. 8.22a on p. 442, high n values are desirable because for the same tool life, we can cut at higher speeds, thus increasing productivity. Conversely, it can also be seen that for the same cutting speed, high n values give longer tool life. Note that as n approaches zero, tool life becomes extremely sensitive to cutting speed, with rapidly decreasing tool life.

8.47 Are there any machining operations that cannot be performed on (a) machining centers and (b) turning centers? Explain.

By the student. By the student; see Section 8.11. In theory, every cutting operation can be performed on a machining center, if we consider the term in its broadest sense, but in practice, there are many that are not reasonable to perform. For example, turning would not be performed on a machining center, nor would boring; for these, turning centers are available.

8.48 What is the significance of the cutting ratio in machining?

Note that the cutting ratio is easily calculated by measuring the chip thickness, while the undeformed chip thickness is a machine setting. Once calculated, the shear angle can be directly obtained through Eq. (8.1) on p. 420, and thus more knowledge is obtained on cutting mechanics, as described in detail in Section 8.2.

8.49 Emulsion cutting fluids typically consist of 95% water and 5% soluble oil and chemical additives. Why is the ratio so unbalanced? Is the oil needed at all? Explain.

The makeup of emulsions reflects the fact that machining fluids have, as their primary purpose, the cooling of the cutting zone (water being an excellent coolant). However, the oil is still necessary; it can attach itself to surfaces and provide boundary lubrication, especially if the cutting process is interrupted, as in milling. See also Section 8.7.

8.50 It was stated that it is possible for the n value in the Taylor tool-life equation to be negative. Explain.

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In machining steel with carbides, for example, it has been noted that at low speeds wear is high, while at intermediate speeds it is much lower. Thus, at low speeds, the Taylor tool-life equation may have a negative value of n. A probable reason is that low cutting speeds allow for greater interaction between the tool and the workpiece, thus causing higher wear. This topic can be a good term paper for students.

8.51 Assume that you are asked to estimate the cutting force in slab milling with a straight-tooth cutter. Describe the procedure that you would follow.

By the student. The student should first make a large, neat sketch of the cutter tooth-workpiece interaction, based on Fig. 8.53a on p. 483; then consider factors such as rake angle, shear angle, varying chip thickness, finite length of chip, etc., remembering that the depth of cut is very small compared to the cutter diameter. See also Section 8.2.

8.52 Explain the possible reasons that a knife cuts better when it is moved back and forth. Consider factors such as the material being cut, interfacial friction, and the shape and dimensions of the knife.

By the student. One obvious effect is that the longitudinal movement of the knife reduces the vertical component of the friction force vector, thus the material being cut is not dragged downward. (Consider, for example, cutting a block of relatively cheese with a wide knife and the considerable force required to do so.) Another factor is the roughness of the cutting edge of the knife. No matter how well it is sharpened and how smooth it appears to be, it still has some finite roughness which acts like the cutting teeth of a very fine saw (as can be observed under high magnification). The students is encouraged to inspect the cutting edge of knives, especially sharp ones, under a microscope and run some simple cutting experiments and describe their observations.

8.53 What are the effects of lowering the friction at the tool-chip interface (say with an effective cutting fluid) on the mechanics of cutting operations? Explain, giving several examples.

The most obvious effect of lowering friction through application of a more effective coolant/lubricant is that the cutting and normal forces will be reduced. Also, the shear angle will be affected [see Eq. (8.20) on p. 433], so that the cutting ratio will be significantly different. This also implies that the chip will undergo a different shear strain, and that chip morphology is likely to be different. The student should elaborate further on this topic.

8.54 Why is it not always advisable to increase cutting speed in order to increase production rate? Explain.

From the Taylor tool-life equation, $VT^n = C$, it can be seen that tool wear increases rapidly with increasing speed. When a tool wears excessively, it causes poor surface finish and higher temperatures. With continual tool replacement, more time is spent indexing or changing tools than is gained through faster cutting. Thus, higher speeds can lead to lower production rates.

8.55 It has been observed that the shear-strain rate in metal cutting is high even though the cutting speed may be relatively low. Why?

By the student. The reason is explained in Section 8.2, and is associated with Eqs. (8.6) and (8.7) on p. 421.

8.56 We note from the exponents in Eq. (8.30) that the cutting speed has a greater influence on temperature than does the feed. Why?

The difference is not too large; it is likely due to the fact that as cutting speed increases, there is little time for the energy dissipated to be conducted or dissipated from the tool. The feed has a lower effect because its speed is so much lower than the cutting speed.

8.57 What are the consequences of exceeding the allowable wear land (see Table 8.5) for cutting tools? Explain.

The major consequences would be:

(a) As the wear land increases, the wear flat will rub against the machined surface and thus temperature will increase due to friction.

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(b) Surface damage may result and dimensional control will become difficult.

(c) Some burnishing may also take place on the machined surface, leading to residual stresses and temperature rise.

(d) Cutting forces will increase because of the increased wear land, requiring greater power for the same machining operation.

8.58 Comment on and explain your observations regarding Figs. 8.34, 8.38, and 8.43.

By the student. For example, from Fig. 8.34 on p. 458 it is clear that edge strength can be obtained from tool geometry; from Fig. 8.38 on p. 461, it is clear that strength is also obtained through the tool material used. Figure 8.43 on p. 472 shows the allowable speeds and feeds for different materials; the materials generally correspond to the strengths given in Fig. 8.38. The range in feeds and speeds can be explained by the range of strengths for different tool geometries in Fig. 8.34.

8.59 It will noted that the tool-life curve for ceramic cutting tools in Fig. 8.22a is to the right of those for other tools. Why?

Ceramic tools are harder and have higher resistance to temperature; consequently, they resist wear better than other tool materials shown in the figure. Ceramics are also chemically inert, even at the elevated temperatures of machining. The high hardness leads to abrasive wear resistance, and the chemical inertness leads to adhesive wear resistance.

8.60 In Fig. 8.18, it can be seen that the percentage of the energy carried away by the chip increases with cutting speed. Why?

Heat is removed from the cutting zone mainly by conduction through the workpiece, chip, and tool. Also note the temperature distribution shown in Fig. 8.16 on p. 437 and how high the temperatures are. Consequently, as the cutting speed increases, the chip will act more and more as a heat sink and carry away much of the heat generated in the cutting zone, and less and less of the heat will be conducted away to the tool or the workpiece.

8.61 How would you go about measuring the effectiveness of cutting fluids? Explain.

By the student. The most effective and obvious method is to test different cutting fluids in actual machining operations. Other methods are to heat the fluids to the temperatures typically encountered in machining, and measure their viscosity and other relevant properties such as lubricity, specific heat, and chemical reactions (see Chapter 4 for details). The students are encouraged to develop their own ideas for such tests.

8.62 Describe the conditions that are critical in benefiting from the capabilities of diamond and cubic-boron-nitride cutting tools.

Because diamond and cBN are brittle, impact due to factors such as cutting-force fluctuations and poor quality of the machine tools used are important. Thus, interrupted cutting (such as milling or turning spline shafts) should be avoided as much as possible. Machine tools should have sufficient stiffness to avoid chatter and vibrations (see Section 8.12). Tool geometry and setting is also important to minimize stresses and possible chipping. The workpiece material must be suitable for diamond or cBN; for example, carbon is soluble in iron and steels at elevated temperatures as encountered in cutting, and therefore diamond would not be suitable for these materials.

8.63 The last two properties listed in Table 8.6 can be important to the life of the cutting tool. Explain why. Which of the properties listed are the least important in machining operations? Explain.

Thermal conductivity is important because with increasing thermal conductivity, heat is conducted away from the cutting zone more quickly through the tool, leading to lower temperatures and hence lower wear. Coefficient of thermal expansion is especially significant for thermal fatigue and for coated tools, where the coating and the substrate must have similar thermal expansion coefficients to avoid large thermal stresses. Of the material properties listed, density, elastic modulus, and melting temperature are the least important.

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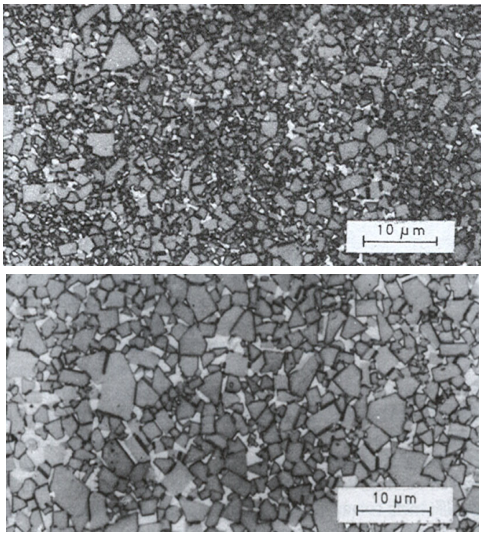
8.64 It will be noted in Fig. 8.30 that the tool materials, especially carbides, have a wide range of hardness at a particular temperature. Why?

By the student. There are various reasons for the range of hardness, including the following:

- All of the materials can have variations in their microstructure, thus significantly affecting hardness. For example, compare the following two micrographs of tungsten carbide, showing a fine-grained (left) and coarse-grained (right) tungsten carbide. (*Source:* Trent, E.M., and Wright, P.K., *Metal Cutting* 4th ed., Butterworth Heinemann, 2000, pp. 178-185).



- There can be a wide range in the concentration of the carbide as compared to the cobalt binder.
- For materials such as carbon tool steels, the carbon content can be different, as can the level of case hardening of the tool.
- High-speed steels and ceramics are generic terms, with a wide range of individual chemistries and compositions.

8.65 Describe your thoughts on how would you go about recycling used cutting tools. Comment on any difficulties involved, as well as on economic considerations.

By the student. Recycling is a complicated subject and involves economic as well as environmental considerations (see also pp. 12-15). Fortunately, cutting-tool materials are generally non-toxic (with the exception of cobalt in carbide tools), and thus they can be disposed of safely. The main consideration is economics: Is recycling of the tool material cost effective? Considerations include energy costs in recycling the tool and processing costs in refurbishment, compared to the material costs savings. This is an appropriate topic for a student term paper.

8.66 As you can see, there is a wide range of tool materials available and used successfully today, yet much research and development continues to be carried out on these materials. Why?

By the student. The reasons for the availability of a large variety of cutting-tool materials is best appreciated by reviewing Table 8.6 on p. 454. Among various factors, the type of workpiece material machined, the type of machining operation, and the surface finish and dimensional accuracy required all affect the choice of a cutting-tool material. For example, for interrupted cutting operations such as milling, we need toughness and impact strength. For operations where much heat is generated due, for example, to high cutting speeds, hot hardness is important. If very fine surface finish is desired, then ceramics and diamond would be highly desirable. Tool materials continue to be investigated further because, as in all other materials, there is much progress to be made for reasons such as to improve consistency of properties, extend their applications, develop new tool geometries, and reduce costs. The students are encouraged to comment further on this topic.

8.67 Drilling, boring, and reaming of large holes is generally more accurate than just drilling and reaming. Why?

The boring process has generally better control of dimensional accuracy than drilling because of the overall stiffness of the setup. However, a boring tool requires an initial hole, so the drilling step cannot be eliminated. Reaming is a generally slow process and produces good surface finish on a precisely produced hole.

8.68 A highly oxidized and uneven round bar is being turned on a lathe. Would you recommend a

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relatively small or large depth of cut? Explain your reasons.

Because oxides are generally hard and abrasive (see p. 146), light cuts will cause the tool to wear rapidly, and thus it is highly desirable to cut right through the oxide layer during the first pass. Note that an uneven round bar indicates significant variations in the depth of cut being taken; thus, depending on the degree of eccentricity, it may not always be possible to do so since this can lead to self-excited vibration and chatter.

8.69 Does the force or torque in drilling change as the hole depth increases? Explain.

Both the torque and the thrust force generally increase as the hole depth increases, although the change is more pronounced on the torque. Because of elastic recovery along the cylindrical surface of the hole, there is a normal stress exerted on the surface of the drill while in the hole. Consequently, the deeper the hole, the larger the surface area and thus the larger the force acting on the periphery of the drill, leading to a significant increase in torque.

8.70 Explain the advantages and limitations of producing threads by forming and cutting, respectively.

By the student. Thread rolling is described in Section 6.3.5. The main advantages of thread rolling over thread cutting are the speeds involved (thread rolling is a very high-production-rate operation). Also, the fact that the threads undergo extensive cold working will lead to stronger work-hardened threads. Cutting continues to be used for making threads because it is a very versatile operation and much more economical for low production runs (since expensive dies are not required). Note that internal threads also can be rolled, but this is not nearly as common as machining and can be a difficult operation to perform.

8.71 Describe your observations regarding the contents of Tables 8.8, 8.10, and 8.11.

By the student. Note, for example, that the side rake angle is low for the ductile materials such as thermoplastics, but is high for materials more difficult to machine, such as refractory alloys and some cast irons with limited ductility. Similar observations can be made for the drill geometries and the point angle.

8.72 The footnote to Table 8.10 states that as the depth of the hole increases, speeds and feeds should be reduced. Why?

As hole depth increases, elastic recovery in the workpiece causes normal stresses on the surface of the drill, thus the stresses experienced by the drill are higher than they are in shallow holes. These stresses, in turn, cause the torque on the drill to increase and may even lead to its failure. Reduction in feeds and speeds can compensate for these increases. (See also answer to Question 8.69.)

8.73 List and explain the factors that contribute to poor surface finish in machining operations.

By the student. As an example, one factor is explained by Eq. (8.35) on p. 449, which gives the roughness in a process such as turning. Clearly, as the feed increases or as the tool nose radius decreases, roughness will increase. Other factors that affect surface finish are built-up edge (see, for example, Figs. 8.4 and 8.6), dull tools or tool-edge chipping (see Fig. 8.28), or vibration and chatter (Section 8.11.1).

8.74 Make a list of the machining operations described in this chapter, according to the difficulty of the operation and the desired effectiveness of cutting fluids. (*Example:* Tapping of holes is a more difficult operation than turning straight shafts.)

By the student. Tapping is high in operational severity because the tool produces chips that are difficult to dispose of. Tapping has a very confined geometry, making effective lubrication and cooling difficult. Turning, on the other hand, is relatively easy.

8.75 Are the feed marks left on the workpiece by a face-milling cutter segments of a true circle? Explain with appropriate sketches.

By the student. Note that because there is always movement of the workpiece in the feed direction, the feed marks will not be segments of true circles.

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8.76 What determines the selection of the number of teeth on a milling cutter? (See, for example, Figs. 8.53 and 8.55.)

The number of teeth will affect the surface finish produced, as well as vibrations and chatter, depending on the machine-tool structural characteristics. The number is generally chosen to achieve the desired surface finish at a given set of machining parameters. Note also that the finer the teeth, the greater the tendency for chip to clog. At many facilities, the choice of a cutter may simply be what tooling is available in the stock room.

8.77 Explain the technical requirements that led to the development of machining and turning centers. Why do their spindle speeds vary over a wide range?

By the student. See Section 8,11. Briefly, machining centers, as a manufacturing concept, serve two basic purposes:

(a) save time by rapid tool changes,

(b) eliminating part handling and mounting in between operations, and

(c) rapid changeover for machining different parts in small lots.

Normally, much time would be spent transferring and handling the workpiece between different machine tools. Machining centers eliminate or greatly reduce the need for part handling and, consequently, reduce manufacturing time and costs.

8.78 In addition to the number of components, as shown in Fig. 8.74, what other factors influence the rate at which damping increases in a machine tool? Explain.

By the student. The most obvious factors are the damping characteristics of the machine-tool structure and its foundation; vibration isolating pads are commonly installed under machine tools. The type and quality of joints, as well as the quality of the sliding surfaces and their lubrication, and the manner in which the individual components are assembled also have a significant effect. (See Section 8.11.1.)

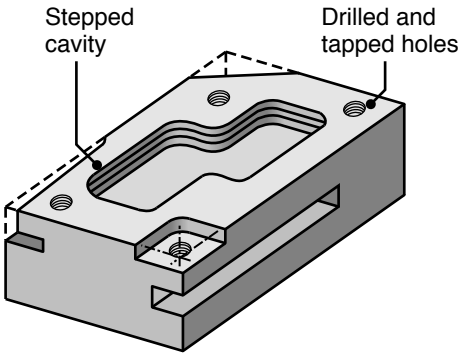
8.79 Why is thermal expansion of machine-tool components important? Explain, with examples.

When high precision is required, thermal distortion is very important and must be eliminated or minimized. This is a serious concern, as even a few degrees of temperature rise can be significant and can compromise dimensional accuracy. The student should elaborate further.

8.80 Would using the machining processes described in this chapter be difficult on nonmetallic or rubber like materials? Explain your thoughts, commenting on the influence of various physical and mechanical properties of workpiece materials, the cutting forces involved, the parts geometries, and the fixturing required.

By the student. Rubber like materials are difficult to machine mainly because of their low elastic modulus and very large elastic strains that they can undergo under external forces. Care must be taken to properly support the workpiece and minimize the cutting forces. Note also that these materials become stiffer with lower temperatures, which suggests an effective cutting strategy and chilling of the workpiece.

8.81 The accompanying illustration shows a part that is to be machined from a rectangular blank. Suggest the type of operations required and their sequence, and specify the machine tools that are needed.



By the student. The main challenge with the part shown is in designing a fixture that allows all of the operations to be performed without interference. Clearly, a milling machine will be required for milling the stepped cavity and the

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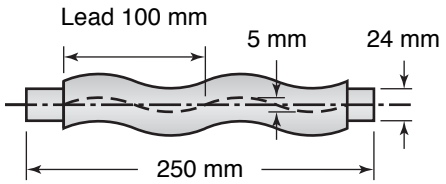
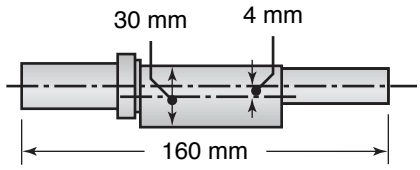
slots; the holes could be produced in the milling machine as well, although a drill press may be used instead. Note that one hole is drilled on a milled surface, so drilling and tapping have to follow milling. If the surface finish on the exterior is not critical, a chuck or vise can be used to grip the surface at the corners, which is plausible if the part has sufficient height. The grips usually have rough surfaces, so they will leave marks which will be more pronounced in aluminum than in stainless steels.

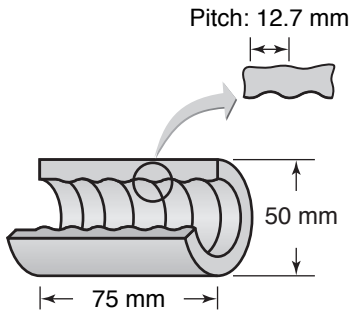
8.82 Select a specific cutting-tool material and estimate the machining time for the parts shown in the accompanying three figures: (a) pump shaft, stainless steel; (b) ductile (nodular) iron crankshaft; (c) 304 stainless-steel tube with internal rope thread.



(a)



(b)



(c)

By the student. Students should address the methods and machinery required to produce these components, recognizing the economic implications of their selection of materials.

8.83 Why is the machinability of alloys generally difficult to assess?

The machinability of alloys is difficult to assess because of the wide range of chemical, mechanical, and physical properties that can be achieved in alloys, as well as their varying amounts of alloying elements. Some mildly alloyed materials may be machined very easily, whereas a highly alloyed material may be brittle, abrasive, and thus difficult to machine.

8.84 What are the advantages and disadvantages of dry machining?

By the student. See Section 8.7.2. The advantages of dry machining include:

(a) no lubricant cost;
(b) no need for lubricant disposal;
(c) no environmental concerns associated with lubricant disposal;
(d) no need to clean the workpiece, or at least the cleaning is far less difficult.

The disadvantages include:

(a) possibly higher tool wear;
(b) oxidation and discoloration of the workpiece surface since no lubricant is present to protect surfaces;
(c) possibly higher thermal distortion of the workpiece, and
(d) washing away chips may become difficult.

8.85 Can high-speed machining be performed without the use of cutting fluids? Explain.

This can be done, using appropriate tool materials and processing parameters. Recall that in high speed machining, most of the heat is conveyed from the cutting zone through the chip, so the need for a cutting fluid is less.

8.86 If the rake angle is 0°, then the frictional force is perpendicular to the cutting direction and, therefore, does not contribute to machining power requirements. Why, then, is there an increase in the power dissipated when machining with a rake angle of, say, 20°?

Lets first note that although the frictional force, because of its vertical position, does not directly affect the cutting power at a rake angle of zero,

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it does affect it indirectly by influencing the shear angle. Recall that the higher the friction, the lower the shear angle and the higher the energy required. As the rake angle increases, say to 20°, the friction force (see Fig. 8.11 on p. 428) will now affect the position of the resultant force, R, and thus have a component contributing to the cutting force. These complex interactions result in the kind of force variations, as a function of rake angle, shown in Tables 8.1 and 8.2 on pp. 430-431.

8.87 Would you recommend broaching a keyway on a gear blank before or after the teeth are machined? Explain.

By the student. The keyway should be machined before the teeth is machined. The reason is that in hobbing or related processes (see Section 8.10.7), the gear blank is indexed. The keyway thus serves as a natural guide for indexing the blank.

8.88 Given your understanding of the basic metal-cutting process, describe the important physical and chemical properties of a cutting tool.

By the student. Generally, the important properties are hardness (especially hot hardness), toughness, thermal conductivity, and thermal expansion coefficient. Chemically, the tool must be inert to the workpiece material at the cutting temperatures developed. See also Section 8.6 and Table 8.6 on p. 454.

8.89 Negative rake angles are generally preferred for ceramic, diamond, and cubic boron nitride tools. Why?

By the student. Although hard and strong in compression, these materials are brittle and relatively weak in tension. Consequently, negative rake angles, which indicate larger included angle of the tool tip (see, for example, Fig. 8.2 on p. 419) are preferred mainly because of the lower tendency to cause tensile stresses and chipping of the tools.

8.90 If a drill bit is intended for woodworking applications, what material is it most likely to be made from? (*Hint:* Temperatures rarely rise to 400°C in woodworking.) Are there any reasons why such a drill bit cannot be used to drill a few holes in a piece of metal? Explain.

Because of the lower forces and temperatures involved, as well as economic considerations, woodworking tools are typically made of carbon steels, with some degree of hardening by heat treatment. Note from Fig. 8.30 on p. 453 that carbon steels maintain a reasonably high hardness for temperatures less than 400oF. For drilling metals, however, the temperatures are high enough to significantly soften the carbon steel (unless drilling at low rotational speeds), thus quickly dulling the drill bit.

8.91 What are the consequences of a coating on a cutting tool that has a different coefficient of thermal expansion than does the substrate? Explain.

Consider the situation where a cutting tool and the coating are stress-free at room temperature when the tool is inserted; then consider the situation when the tool is used in cutting and the temperatures are very high. A mismatch in thermal expansion coefficients will cause high thermal strains at the temperatures developed during machining. This can result in a separation (delamination) of the coating from the substrate. (See also pp. 107-108.)

8.92 Discuss the relative advantages and limitations of near-dry machining. Consider all relevant technical and economic aspects.

The advantages are mostly environmental as there is no cutting fluid involved, which would add to the manufacturing cost, or to dispose of or treat before its disposal. This has other implications in that the workpiece doesn't have to be cleaned, so no cleaning fluids, such as solvents, have to be used. Also, lubricants are expensive and difficult to control. However, cutting-fluid residues provide a protective oil film on the machined surfaces, especially with freshly machined metals that begin to rapidly oxidize, as described in Section 4.2. (See also answer to Question 8.84.)

8.93 In modern manufacturing with computer-controlled machine tools, which types of metal chips are undesirable and why?

By the student. Continuous chips are not desirable because (a) the machines are now mostly untended and operate at high speeds, thus chip

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generation is at a high rate (see also chip collection systems, p. 700) and (b) continuous chips would entangle on spindles and machine components, and thus severely interfere with the machining operation. Conversely and for that reason, discontinuous chips or segmented chips would be desirable, and indeed are typically produced using chip-breaker features on tools, Note, however, that such chips can lead to vibration and chatter, depending on the workpiece material, processing parameters, and the characteristics of the machine tool (see p. 487).

8.94 Explain why hacksaws are not as productive as band saws.

A band saw has continuous motion, whereas a hacksaw reciprocates. About half of the time, the hacksaw is not producing any chips, and thus it is not as productive.

8.95 Describe workpieces and conditions under which broaching would be the preferred method of machining.

By the student. Broaching is very attractive for producing various external and internal geometric features; it is a high-rate production process and can be highly automated. Although the broach width is generally limited (see p. 491), typically a number of passes are taken to remove a volume of material, such as on the top surface of engine blocks. Producing notches, slots, or keyways are common applications where broaching is very useful.

8.96 With appropriate sketches, explain the differences between and similarities among the following processes: (a) shaving, (b) broaching, and (c) turn broaching.

By the student. Note, for example, that the similarities are generally in the mechanics of cutting, involving a finite-width chip and usually orthogonal. The differences include particulars of tooling design, the machinery used, and workpiece shapes.

8.97 Why is it difficult to use friction sawing on nonferrous metals? Explain.

As stated in Section 8.10.5, nonferrous metals have a tendency to adhere to the blade, caused by adhesion at the high temperatures and attributable to the softness of these materials. Note also that these materials typically have high thermal conductivity, so if the metal has melted, it will quickly solidify and make the operation more difficult.

8.98 Review Fig. 8.68 on modular machining centers, and explain workpieces and operations that would be suitable on such machines.

By the student. The main advantages to the different modular setups shown in Fig. 8.68 on p. 498 are that various workpiece shapes and sizes can be accommodated and the tool support can be made stiffer by minimizing the overhang. (See Section 8.11.3 for the benefits of reconfigurable machines.)

8.99 Describe types of workpieces that would not be suitable for machining on a machining center. Give specific examples.

By the student. There are some workpieces that cannot be produced on machining centers, as by their nature they are very flexible. Consider, for example:

- Workpieces that are required in much higher quantities than can be performed economically on machining centers.
- Parts that are too large for the machining-center workspace, such as large forgings or castings.
- Parts that require specialized machines, such as rifling of gun barrels.

8.100 Give examples of (a) forced vibration and (b) self-excited vibration in general engineering practice.

By the student. See Section 8.12. Simple examples of forced vibration are a punching bag, a pogo stick, vibrating pages and cell phones, and timing clocks in computers. Examples for self-excited vibration include musical instruments and human speech. The collapse of the Tacoma Narrows Bridge in Washington State in 1940 is a major example of self-excited vibration. (See also engineering texts on vibration.)

8.101 Tool temperatures are low at low cutting speeds and high at high cutting speeds, but low again at even higher cutting speeds. Explain why.

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At low cutting speeds, energy is dissipated in the shear plane and at the chip-tool interface, and conducted through the workpiece and/or tool and eventually to the environment (see also Fig. 8.18 on p. 439). At higher speeds, conduction cannot take place rapidly enough. At even higher speeds, the heat will be carried away by the chip, hence the workpiece will remain cooler. This is one of the major advantages of high speed machining, described in Section 8.8.

8.102 Explain the technical innovations that have made high-speed machining advances possible, and the economic motivations for high-speed machining.

This topic is described in Section 8.8. The technical advances that have made high-speed machining possible include the availability of advanced cutting-tool materials, design of machine tools, stiff and lightweight spindles, and advanced methods of chip disposal. The economic motivations for high-speed machining are that dimensional tolerances can be improved, mainly because of the absence or reduction of thermal distortion, and the labor cost per part can be greatly reduced.

Problems

8.103 Assume that in orthogonal cutting the rake angle is 15° and the coefficient of friction is 0.2. Using Eq. (8.20), determine the percentage increase in chip thickness when friction is doubled.

We begin with Eq. (8.1) on p. 420 which shows the relationship between chip thickness and depth of cut. Assuming that the depth of cut and the rake angle are constant, we can rewrite this equation as

$$\frac{t_o}{t_c} = \frac{\cos(\phi_2 - \alpha)\sin\phi_2}{\cos(\phi_1 - \alpha)\sin\phi_2}$$

Now, using Eq. (8.20) on p. 433 we can estimate the two shear angles. For Case 1, we have from Eq. (8.12) on p. 429 that $\mu = 0.2 = \tan\beta$, or $\beta = 11.3°$, and hence

$$\phi_1 = 45° + \frac{15°}{2} - \frac{11.3°}{2} = 46.85°$$

and for Case 2, where $\mu = 0.4$, we have $\beta = \tan^{-1} 0.4 = 21.8°$ and hence $\phi_2 = 41.6°$. Substituting these values in the above equation for chip thickness ratio, we obtain

$$\begin{aligned}\frac{t_o}{t_c} &= \frac{\cos(\phi_2 - \alpha)\sin\phi_1}{\cos(\phi_1 - \alpha)\sin\phi_2} \\ &= \frac{\cos(41.6° - 15°)\sin 46.85°}{\cos(46.85° - 15°)\sin 41.6°}\end{aligned}$$

or $t_o/t_c = 1.16$. Therefore, the chip thickness increased by 16%.

8.104 Prove Eq. (8.1).

Refer to the shear-plane length as l and note from Fig. 8.2a on p. 419 that the depth of cut, t_o, is

$$t_o = l\sin\phi$$

Similarly, from Fig. 8.3, the chip thickness is

$$t_c = l\cos(\phi - \alpha)$$

Substituting these relationships into the definition of cutting ratio gives

$$r = \frac{t_o}{t_c} = \frac{l\sin\phi}{l\cos(\phi - \alpha)} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

8.105 With a simple analytical expression prove the validity of the statement in the last paragraph in Example 8.2.

The work involved in tension and machining, respectively, can be expressed as

$$W_{\text{tension}} \propto D_o^2 \left[\ln\left(\frac{D_o}{D_f}\right)^{n+1}\right]$$

and

$$W_{\text{machining}} \propto \left(D_o^2 - D_f^2\right) u_{\text{machining}}$$

Since $u_{\text{machining}}$ is basically a constant, the ratio of W_t/W_m is a function of the original and

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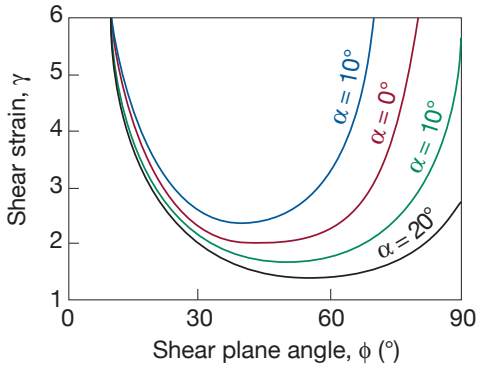
final diameters of the part. Either by inspection of these equations, or by substituting numbers (such as letting $D_o = 0.100$ in and $D_f = 0.080$ in.) and comparing the results, we find that as D_o decreases, the ratio of W_t/W_m increases.

8.106 Using Eq. (8.3), make a plot of the shear strain, γ, vs. the shear angle, ϕ, with the rake angle, α, as a parameter. Describe your observations.

The plot is as follows:



At high shear angles, the effect of α is more pronounced. At low shear angles, the rake angle α has a much lower effect. This can be visualized from the geometry of the cutting zone.

8.107 Assume that in orthogonal cutting, the rake angle is 10°. Plot the shear plane angle and cutting ratio as a function of the friction coefficient.

Note from Eq. (8.12) that $\beta = \tan^{-1}\mu$. The shear angle can be estimated, either from Eq. (8.20) or (8.21), as

$$\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}$$

or

$$\phi = 45^\circ + \alpha - \beta$$

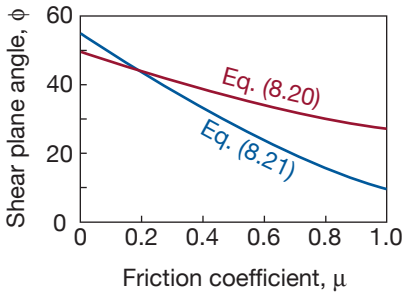
Substituting for α and β gives

$$\phi = 50^\circ - \frac{1}{2}\tan^{-1}\mu$$

or

$$\phi = 55^\circ - \tan^{-1}\mu$$

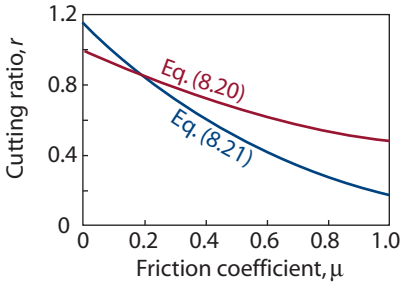
These are plotted as follows:



The cutting ratio is given by Eq. (8.1) on p. 420 as

$$r = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

The two expressions for ϕ can be used to obtain the cutting ratio as a function of μ, which is plotted below. This can be compared to the results for Problem 8.103.



8.108 Derive Eq. (8.12).

From the force diagram in Fig. 8.11a on p. 428, we express the following:

$$F = (F_t + F_c\tan\alpha)\cos\alpha$$

and

$$N = (F_c - F_t\tan\alpha)\cos\alpha$$

Therefore, by definition,

$$\mu = \frac{F}{N} = \frac{(F_t + F_c\tan\alpha)}{(F_c - F_t\tan\alpha)}$$

8.109 Determine the shear angle in Example 8.1. Is this calculation exact or an estimate? Explain.

For the cutting ratio of $r = 0.555$, obtained in Example 8.1 on p. 435, and using Eq. (8.1) on p. 420 , with $\alpha = 10^\circ$, we find that $\phi = 31.17^\circ$. Assuming that shear takes place along a plane,

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this is an exact calculation. If shear takes place in a zone (Fig. 8.2b), this is an approximation. Note that we can estimate ϕ theoretically using Eq. (8.20).

8.110 The following data are available from orthogonal cutting experiments. In both cases, depth of cut (feed) $t_o = 0.13$ mm, width of cut $w = 2.5$ mm, rake angle $\alpha = -5°$, and cutting speed $V = 2$ m/s.

	Workpiece material	
	Aluminum	Steel
Chip thickness, t_c, mm	0.23	0.58
Cutting force, F_c, N	430	890
Thrust force, F_t, N	280	800

Determine the shear angle ϕ [do not use Eq. (8.20)], friction coefficient μ, shear stress τ and shear strain γ on the shear plane, chip velocity V_c and shear velocity V_s, as well as energies u_f, u_s and u_t.

First, consider the aluminum workpiece, where $t_c = 0.23$ mm, $F_c = 430$ N, $F_t = 280$ N, $t_o = 0.13$ mm, $w = 2.5$ mm, $\alpha = -5°$ and $V = 2$ m/s. From Eq. (8.1) on p. 420 ,

$$r = \frac{t_o}{t_c} = \frac{0.13}{0.23} = 0.565$$

Also from Eq. (8.1),

$$\frac{\sin\phi}{\cos(\phi - \alpha)} = r$$

or

$$\frac{\sin\phi}{\cos(\phi + 5°)} = 0.565$$

This equation is solved numerically as $\phi = 28.2°$. From Eq. (8.12), the coefficient of friction is given by

$$\mu = \frac{F_t + F_c \tan\alpha}{F_c - F_t \tan\alpha} = \frac{280 + 430\tan(-5°)}{430 - 280\tan(-5°)}$$

or $\mu = 0.533$. Therefore, $\beta = \tan^{-1}\mu = 28.0°$. To obtain the shear stress on the shear plane, we solve Eq. (8.11) for τ:

$$F_c = \frac{wt_o\tau\cos(\beta - \alpha)}{\sin\phi\cos(\phi + \beta - \alpha)}$$

or

$$\begin{aligned}\tau &= \frac{F_c \sin\phi\cos(\phi + \beta - \alpha)}{wt_o\cos(\beta - \alpha)} \\ &= \frac{(430)\sin 28.2°\cos(28.2° + 28.0° + 5°)}{(0.0025)(0.00013)\cos(28.0° + 5°)} \\ &= 359 \text{ MPa}\end{aligned}$$

From Eq. (8.3) the shear strain is given by

$$\begin{aligned}\gamma &= \cot\phi + \tan(\phi - \alpha) \\ &= \cot 28.2° + \tan(28.2° + 5°) = 2.52\end{aligned}$$

The chip velocity is obtained from Eq. (8.5):

$$\begin{aligned}V_c &= V\frac{\sin\phi}{\cos(\phi - \alpha)} \\ &= (2)\frac{\sin(28.2°)}{\cos(28.2° + 5°)} = 1.13 \text{ m/s}\end{aligned}$$

The shear velocity, V_s, is obtained from Eq. (8.6):

$$V_s = V_c\frac{\cos\alpha}{\sin\phi} = (1.13)\frac{\cos(-5°)}{\sin(28.2°)} = 2.38 \text{ m/s}$$

The energies are given by Eqs. (8.24)-(8.25) and (8.27) as:

$$u_t = \frac{F_c}{wt_o} = \frac{430}{(2.5)(0.13)} = 1323 \text{ MN-m/m}^3$$

$$u_f = \frac{(F_c\sin\alpha + F_t\cos\alpha)r}{wt_o} = 420 \text{ MN-m/m}^3$$

$$u_s = u_t - u_f = 1323 - 419 = 903 \text{ MN-m/m}^3$$

The same approach is used for the steel workpiece, with the following results:

$r_c = 0.224$	$\phi = 12.3°$
$\mu = 0.752$	$\tau = 458$ MPa
$\gamma = 4.90$	$V_c = 0.448$ m/s
$V_s = 2.08$ m/s	$u_t = 2738$ MN-m/m^3
$u_s = 2244$MN-m/m^3	$u_f = 494$ MN-m/m^3

8.111 Estimate the temperatures for the conditions of Problem 8.110 for the following workpiece properties:

	Workpiece material	
	Aluminum	Steel
Flow strength Y_f, MPa	120	325
Thermal diffusivity, K, mm^2/s	97	14
Volumetric specific heat, ρc, N/mm^2°C	2.6	3.3

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From Problem 8.110, we note that $V = 2$ m/s $= 2000$ mm/s and $t_o = 0.13$ mm. Equation (8.29) can be used to calculate the temperature rise, but the equation requires English units. It can be shown that the equivalent form of Eq. (8.29) for SI units is

$$T = \frac{3.8Y_f}{\rho c}\sqrt[3]{\frac{Vt_o}{K}}$$

Therefore, the temperature for the aluminum is given as:

$$T_{\text{al}} = \frac{3.8Y_f}{\rho c}\sqrt[3]{\frac{Vt_o}{K}} = \frac{3.8(120)}{2.6}\sqrt[3]{\frac{(2000)(0.13)}{97}}$$

or $T_{\text{al}} = 244°$C. For steel,

$$T_{\text{s}} = \frac{3.8Y_f}{\rho c}\sqrt[3]{\frac{Vt_o}{K}} = \frac{3.8(325)}{3.3}\sqrt[3]{\frac{(2000)(0.13)}{14}}$$

or $T_{\text{s}} = 990°$C

8.112 In a dry cutting operation using a $-5°$ rake angle, the measured forces were $F_c = 1330$ N and $F_t = 740$ N. When a cutting fluid was used, these forces were $F_c = 1200$ N and $F_t = 710$ N. What is the change in the friction angle resulting from the use of a cutting fluid?

Equation (8.12) allows calculation of the friction angle, β, as:

$$\tan\beta = \frac{F_t + F_c\tan\alpha}{F_c - F_t\tan\alpha}$$

For the initial case,

$$\tan\beta = \frac{740 + (1330)\tan -5°}{1330 - 740\tan -5°} = 0.447$$

Therefore, $\beta = 24.1°$. With a cutting fluid, Eq. (8.12) gives:

$$\tan\beta = \frac{710 + (1200)\tan -5°}{1200 - 710\tan -5°} = 0.479$$

or $\beta = 25.6°$. Thus, the cutting fluid has caused a change in β of 25.6°-24.1° = 1.5°.

8.113 In the dry machining of aluminum with a 10° rake angle tool, it is found that the shear angle is 25°. Determine the new shear angle if a cutting fluid is applied which decreases the friction coefficient by 15%.

From Eq. (8.20) and solving for β,

$$\beta = 90° + \alpha - 2\phi = 90° + 10° - 2(25°) = 50°$$

Therefore, from Eq. (8.12), $\mu = \tan\beta = 1.19$ If the friction coefficient is reduced by 15%, then $\mu = 1.01$, so that $\beta = \tan\mu = 45.4°$. Therefore, from Eq. (8.20),

$$\phi = 45° + \frac{\alpha}{2} - \frac{\beta}{2} = 27.3°$$

8.114 Taking carbide as an example and using Eq. (8.30), determine how much the feed should be changed in order to keep the mean temperature constant when the cutting speed is tripled.

We begin with Eq. (8.32) which, for this case, can be rewritten as

$$V_1^a f_1^b = (3V_1)^a f_2^b$$

Rearranging and simplifying this equation, we obtain

$$\frac{f_2}{f_1} = 3^{-a/b}$$

For carbide tools, approximate values are given on in Section 8.2.6 as $a = 0.2$ and $b = 0.125$. Substituting these values, we obtain

$$\frac{f_2}{f_1} = 3^{-(0.2/0.125)} = 0.17$$

Therefore, the feed should be reduced by (1-0.17) = 0.83, or 83%.

8.115 With appropriate diagrams, show how the use of a cutting fluid can affect the magnitude of the thrust force, F_t, in orthogonal cutting.

Note in Fig. 8.11 on p. 428 that the use of a cutting fluid will reduce the friction force, F, at the tool-chip interface. This, in turn, will change the force diagram, hence the magnitude of the thrust force, F_t. Consider the sketch given below. The left sketch shows cutting without an effective cutting fluid, so that the friction force, F is large compared to the normal force, N. The sketch on the right shows the effect if the friction force is a smaller fraction of the normal force because of the cutting fluid. As can be seen, the cutting force is reduced when using the fluid. The largest effect is on the thrust force, but there is also a noticeable effect on the cutting force, which becomes larger as the rake angle increases.

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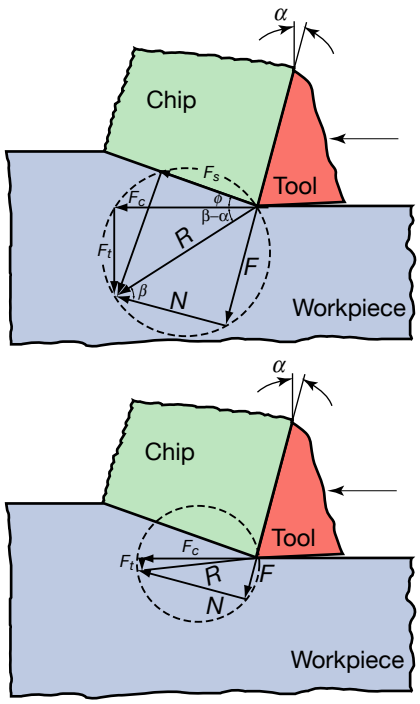

8.116 An 8-in-diameter stainless-steel bar is being turned on a lathe at 600 rpm and at a depth of cut, $d = 0.1$ in. If the power of the motor is 5 hp and has a mechanical efficiency of 80%, what is the maximum feed that you can have at a spindle speed of 500 rpm before the motor stalls?

From Table 8.3 on p. 435, we estimate the power requirement for this material as 1.5 hp-min/in^3 (a mean value for stainless steel). Since the motor has a capacity of 5 hp, the maximum volume of material that can be removed per unit time is 5/1.5 = 3.33 in^3/min. Because the depth of cut is much smaller than the workpiece diameter and referring to Fig. 8.42, we note that the material removal rate in this operation is

$$\text{MRR} = \pi D d f N$$

Thus, the maximum feed can now be calculated as

$$f = \frac{\text{MRR}}{\pi D d N} = \frac{3.33}{\pi(8)(0.1)(600)}$$

or $f = 0.0022$ in./rev.

8.117 Using the Taylor equation for tool wear and letting $n = 0.3$, calculate the percentage increase in tool life if the cutting speed is reduced by (a) 30% and (b) 60%.

The Taylor equation for tool wear is given by Eq. (8.31), which can be rewritten as

$$C = VT^n$$

We can compare two cases as

$$V_1 T_1^n = V_2 T_2^n$$

or

$$\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^n$$

solving for T_1/T_2,

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{1/n}$$

(a) For the case where the speed is reduced by 30%, then $V_2 = 0.7V_1$, and thus

$$\frac{T_1}{T_2} = \left(\frac{0.7V_1}{V_1}\right)^{1/0.3} = 0.30$$

or the new life T_2 is 3.3 times the original life.

(b) For a speed reduction of 60%, the new tool life is $T_2 = 21.2T_1$, or a 2120% increase.

8.118 The following flank wear data were collected in a series of machining tests using C6 carbide tools on 1045 steel (HB=192). The feed rate was 0.015 in./rev and the width of cut was 0.030 in. (a) Plot flank wear as a function of cutting time. Using a 0.015 in. wear land as the criterion of tool failure, determine the lives for the four cutting speeds shown. (b) Plot the results on log-log plot and determine the values of n and C in the Taylor tool life equation. (Assume a straight line relationship.) (c) Using these results, calculate the tool life for a cutting speed of 300 ft/min.

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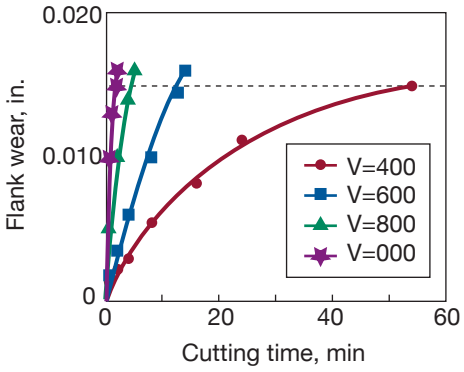
Cutting speed V, ft/min	Cutting time min	Flank wear in.
400	0.5	0.0014
	2.0	0.0023
	4.0	0.0030
	8.0	0.0055
	16.0	0.0082
	24.0	0.0112
	54.0	0.0150
600	0.5	0.0018
	2.0	0.0035
	4.0	0.0060
	8.0	0.0100
	13.0	0.0145
	14	0.0160
800	0.5	0.0050
	2.0	0.0100
	4.0	0.0140
	5.0	0.0160
1000	0.5	0.0100
	1.0	0.0130
	1.8	0.0150
	2.0	0.0160

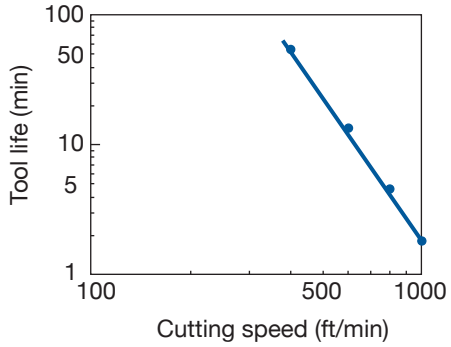
The plot of flank wear as a function of cutting time is as follows:



The 0.015 in. threshold for flank wear is indicated by the dashed line. From this, the following are the estimated tool life:

Speed (ft/min)	Life (min)
400	54
600	13.5
800	4.5
1000	1.8

The log-log plot of cutting speed vs. tool life is as follows:



From which a curve fit suggests $n = 0.262$ and $C = 1190$. Therefore, the Taylor equation for this material is

$$VT^{0.262} = 1190$$

If $V = 300$, then $T = 192$ min.

8.119 Determine the n and C values for the four tool materials shown in Fig. 8.22a.

From Eq. (8.31) on p. 441 note that the value of C corresponds to the cutting speed for a tool life of 1 minute. From Fig. 8.22a, and by extrapolating the tool-life curves to a tool life of 1 min, the C values can be estimated as (ranging from ceramic to HSS): 11,000, 3,000, 400, and 200. Likewise the n values are obtained from the negative inverse slopes, and are estimated as 0.73 (36°), 0.47 (25°), 0.14 (8°), and 0.11 (6°), respectively. Note that these n values compare well with those given in Table 8.4 on p. 442.

8.120 Using Eq. (8.30) and referring to Fig. 8.18a, estimate the magnitude of the coefficient a.

For this problem, assume (although it is not strictly correct) that the mean temperature, T, is equal to the flank surface temperature, as given in Fig. 8.18a. We can then determine the values of temperature as a function of the cutting speed, V, and obtain a curve fit. The particular answers obtained by the students will vary, depending on the distance from the tool tip taken to obtain the estimate. However, as an example, note that at a value of 0.24 in. from the tool tip, we have

Speed (ft/min)	200	300	550
Flank temperature (°F)	900	1030	1270

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The resulting curve fit of the form of Eq. (8.30) on p. 439 gives the value of a as 0.34. Note that this is within a reasonable range of the value given on p. 439.

8.121 (a) Estimate the machining time required in rough turning a 1.5-m-long, annealed aluminum-alloy round bar 75-mm in diameter, using a high-speed-steel tool. (b) Estimate the time for a carbide tool. Let feed = 2 mm/rev.

Let's assume that annealed aluminum alloys can be machined at a maximum cutting speed of 4 m/s using high-speed steel tools and 7 m/s for carbide tools (see Table 8.9 on p. 472). The maximum cutting speed is at the outer diameter, and for high-speed steel it is

$$V = N\pi D$$

or

$$N = \frac{V}{\pi D} = \frac{4}{\pi(0.075)} = 16.97 \text{ rev/s}$$

or $N = 1018$ rpm. For carbide, the speed is 1782 rpm. For a feed of 2 mm/rev, the time to perform one pass is given for high-speed steel by

$$t = \frac{L}{fN} = \frac{1.5}{(0.002)(1018)} = 0.74 \text{ min} = 44 \text{ s}$$

Similarly, the machining time per pass for carbide is 0.42 min or 25 s.

8.122 A 150-mm-long, 75-mm-diameter titanium-alloy rod is being reduced in diameter to 65 mm by turning on a lathe in one pass. The spindle rotates at 400 rpm and the tool is traveling at an axial velocity of 200 mm/min Calculate the cutting speed, material removal rate, time of cut, power required, and the cutting force.

First note that the spindle speed is 400 rpm = 41.89 rad/s. The depth of cut can be calculated from the information given as

$$d = \frac{75 - 65}{2} = 5 \text{ mm}$$

and the feed is

$$f = \frac{200 \text{ mm/min}}{400 \text{ rev/min}} = 0.50 \text{ mm/rev}$$

Therefore, the material removal rate can be calculated from Eq. (8.38) on p. 470 as

$$\begin{aligned} \text{MRR} &= \pi D_{\text{ave}} df N \\ &= \pi(70)(5)(0.50)(400) \\ &= 2.2 \times 10^5 \text{ mm}^3/\text{min} \end{aligned}$$

or MRR=3660 mm^3/s. The actual time to cut is given by Eq. (8.39) as

$$t = \frac{l}{fN} = \frac{150 \text{ mm}}{200 \text{ mm/min}} = 0.75 \text{ min}$$

or $t = 45$ s. From Table 8.3, the unit energy required is between 3.0 and 4.1 W-s/mm^3, so lets use an average value of 3.5 W-s/mm^3. Thus, the power required is

$$P = u(\text{MRR}) = (3.5)(3660) = 12,810 \text{ W}$$

or 12.8 kW. The cutting force, F_c, is the tangential force exerted by the tool. Since power is the product of torque and rotational speed, ω, we have

$$T = \frac{P}{\omega} = \frac{12,810 \text{ W}}{41.89 \text{ rad/s}} = 306 \text{ Nm}$$

Dividing the torque by the average workpiece radius, we have

$$F_c = \frac{T}{D_{\text{ave}}/2} = \frac{306 \text{ Nm}}{0.035 \text{ m}} = 8740 \text{ N}$$

8.123 Calculate the same quantities as in Example 8.4 but for high-strength cast iron and at $N = 500$ rpm. .

The maximum cutting speed is at the outer diameter, D_o, and is obtained from the expression

$$V = \pi DN = \pi(0.500)(300) = 471 \text{ in./min}$$

The cutting speed at the machined diameter is

$$V = \pi DN = \pi(0.480)(300) = 452 \text{ in./min}$$

The depth of cut is unaffected and is $d = 0.010$ in. The feed is

$$f = \frac{v}{N} = \frac{8 \text{ in./min}}{300 \text{ rpm}} = 0.0267 \text{ in/rev}$$

Thus, according to Eq. (8.38), the material removal rate is

$$\begin{aligned} \text{MRR} &= \pi D_{\text{ave}} df N \\ &= \pi(0.490)(0.010)(0.02)(300) \\ &= 0.0924 \text{ in}^3/\text{min} \end{aligned}$$

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The actual time to cut, according to Eq. (8.39), is

$$t = \frac{l}{fN} = \frac{6}{0.0267}300 = 0.75 \text{ min} = 45 \text{ s}.$$

The power required can be calculated by referring to Table 8.3. Taking a value for high strength cast iron as 2.0 hp-min/in^3, the power dissipated is

$$P = (2.0)(0.0924) = 0.1848 \text{ hp}$$

and since 1 hp = 396,000 in.-lb/min, the power is 73,180 in.-lb/min. The cutting force, F_c, is the tangential force exerted by the tool. Since power is the product of torque, T, and rotational speed in radians per unit time, we have

$$T = \frac{73,180}{(300)2\pi} = 38.8 \text{ in.-lb}$$

Since $T = (F_c)(D_{\text{avg}}/2)$,

$$F_c = \frac{T}{D_{\text{ave}}/2} = \frac{38.8}{0.490/2} = 158 \text{ lb}$$

8.124 A 0.75-in-diameter drill is being used on a drill press operating at 300 rpm. If the feed is 0.005 in./rev, what is the material removal rate? What is the MRR if the drill diameter is tripled?

The metal removal rate for drilling is given by Eq. (8.40) on p. 480 as

$$\begin{aligned} \text{MRR} &= \frac{\pi D^2}{4} fN \\ &= \frac{\pi(0.75)^2}{4}(0.005)(300) \\ &= 0.66 \text{ in}^3/\text{min} \end{aligned}$$

If the drill diameter is tripled (that is, it is now 2.25 in.), then the metal removal rate is

$$\begin{aligned} \text{MRR} &= \frac{\pi D^2}{4} fN \\ &= \frac{\pi(2.25)^2}{4}(0.005)(300) \\ &= 5.96 \text{ in}^3/\text{min} \end{aligned}$$

It can be seen that this is a ninefold increase in metal removal rate.

8.125 A hole is being drilled in a block of magnesium alloy with a 15-mm drill at a feed of 0.1 mm/rev. The spindle is running at 500 rpm. Calculate the material removal rate, and estimate the torque on the drill.

The material removal rate can be calculated from Eq. (8.40) as

$$\begin{aligned} \text{MRR} &= \frac{\pi D^2}{4} fN \\ &= \frac{\pi(15 \text{ mm})^2}{4}(0.1 \text{ mm/rev})(500 \text{ rpm}) \\ &= 8840 \text{ mm}^3/\text{min} \end{aligned}$$

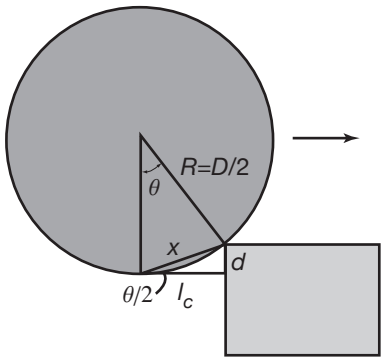
or 147 mm^3/s. Referring to Table 8.3, lets take an average specific energy of 0.5 W-s/mm^3 for magnesium alloys. Therefore

$$P = \left(0.5 \text{ W-s/mm}^3\right)\left(147 \text{ mm}^3/\text{s}\right) = 73.5 \text{ W}$$

Power is the product of the torque on the drill and the rotational speed in radians per second, which, in this, case is (500 rpm)(2π)/60=52.36 rad/s. Therefore, the torque is

$$T = \frac{P}{\omega} = \frac{73.5 \text{ W}}{52.36 \text{ rad/s}} = 1.40 \text{ Nm}$$

8.126 Show that the distance l_c in slab milling is approximately equal to $\sqrt{Dd}$ for situations where $D \gg d$.



Referring to the figure given above, the hypotenuse of the right triangle is assigned the value of x. From the triangle sketched inside the tool,

$$\sin\frac{\theta}{2} = \frac{x/2}{R} = \frac{x}{2R}$$

From the lower triangle,

$$\sin\frac{\theta}{2} = \frac{d}{x}$$

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Thus, eliminating $\sin\frac{\theta}{2}$,

$$\frac{x}{2R} = \frac{d}{x}$$

or, solving for x,

$$x = \sqrt{2Rd} = \sqrt{Dd}$$

From the lower triangle,

$$\cos\frac{\theta}{2} = \frac{l_c}{x}$$

If θ is small, then $\cos\frac{\theta}{2}$ can be taken as 1. Therefore, $l_c \approx x$, and

$$l_c = \sqrt{Dd}$$

8.127 Calculate the chip depth of cut in Example 8.6.

The chip depth of cut, t_c, is given by Eq. (8.42) as

$$t_c = 2f\sqrt{\frac{d}{D}} = 2(0.1)\sqrt{\frac{0.125}{2}} = 0.05 \text{ in.}$$

8.128 In Example 8.6, which of the quantities will be affected when the spindle speed is increased to 200 rpm?

By the student. The quantities affected will be workpiece speed, v, torque, T, cutting time, t, material removal rate, and power.

8.129 A slab-milling operation is being carried out on a 20-in.-long, 6-in.-wide high-strength-steel block at a feed of 0.01 in./tooth and a depth of cut of 0.15 in. The cutter has a diameter of 2.5 in, has six straight cutting teeth, and rotates at 150 rpm. Calculate the material removal rate and the cutting time, and estimate the power required.

From the data given we can calculate the workpiece speed, v, from Eq. (8.43) as

$$v = fNn = (0.01)(150)(6) = 9 \text{ in./min}$$

Using Eq. (8.45) on p. 484, the material removal rate is

$$\text{MRR} = wdv = (6)(0.15)(9) = 8.1 \text{ in}^3\text{/min}$$

Since the workpiece is high-strength steel, the specific energy can be estimated from Table 8.3 as 3.4 hp-min/in^3, as this is the largest value in the range given. Therefore,

$$P = \left(3.4 \text{ hp-min/in}^3\right)\left(8.1\text{in}^3\text{/min}\right) = 27.5 \text{ hp}$$

The cutting time is given by Eq. (8.44) in which the quantity l_c can be shown to be (see answer to Problem 8.126)

$$l_c = \sqrt{Dd} = \sqrt{(2.5)(0.15)} = 0.61 \text{ in.}$$

Therefore the cutting time is

$$t = \frac{l + l_c}{v} = \frac{20 \text{ in.} + 0.61 \text{ in.}}{9 \text{ in./min}} = 2.29 \text{ min}$$

8.130 Referring to Fig. 8.54, assume that $D = 200$ mm, $w = 30$ mm, $l = 600$ mm, $d = 2$ mm, $v = 1$ mm/s, and $N = 200$ rpm. The cutter has 10 inserts, and the workpiece material is 304 stainless steel. Calculate the material removal rate, cutting time, and feed per tooth, and estimate the power required.

The cross section of the cut is

$$wd = (30)(2) = 60 \text{ mm}^2$$

Noting that the workpiece speed is $v = 1$ mm/s, the material removal rate can be calculated as

$$\text{MRR} = (60 \text{ mm}^2)(1 \text{ mm/s}) = 60 \text{ mm}^3\text{/s}$$

The cutting time is given by Eq. (8.44) in which the quantity l_c can be shown to be (see answer to Problem 8.126)

$$l_c = \sqrt{Dd} = \sqrt{(200)(2)} = 20 \text{ mm}$$

Therefore, the cutting time is

$$t = \frac{l + l_c}{v} = \frac{600 \text{ mm} + 20 \text{ mm}}{1 \text{ mm/s}} = 620 \text{ s}$$

The feed per tooth is obtained from Eq. (8.43). Noting that $N = 200$ rpm $= 3.33$ rev/s and the number of inserts is 10, we have

$$f = \frac{v}{Nn} = \frac{1 \text{ mm/s}}{(3.33 \text{ rev/s})(10)} = 0.030 \text{ mm/tooth}$$

For 304 stainless steel, the unit power can be estimated from Table 8.3 as 4 W-s/mm^3. Therefore,

$$P = (4 \text{ W-s/mm}^3)(60 \text{ mm}^3\text{/s}) = 240 \text{ W}$$

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8.131 Estimate the time required for face milling an 8-in.-long, 3-in.-wide brass block using a 8-in-diameter cutter with 12 HSS teeth.

Using the high-speed-steel tool, let's take a recommended cutting speed for brass (a copper alloy) at 90 m/min = 1.5 m/s, or 59 in./s (see Table 8.12 on p. 489), and the maximum feed per tooth as 0.5 mm, or 0.02 in., The rotational speed of the cutter is then calculated from

$$V = \pi DN$$

or, solving for N,

$$N = \frac{V}{\pi D} = \frac{59 \text{ in./s}}{\pi(8 \text{ in.})} = 2.34 \text{ rev/s} = 131 \text{ rpm}$$

The workpiece speed can be obtained from Eq. (8.43) as

$$v = fNn = (0.02 \text{ in.})(141 \text{ rpm})(12)$$

or $v = 0.56$ in./s. The cutting time is given by Eq. (8.44) in which the quantity l_c can be shown to be (see answer to Problem 8.126)

$$l_c = \sqrt{Dd} = \sqrt{(8)(3)} = 4.90 \text{ in.}$$

Therefore the cutting time is

$$t = \frac{l + l_c}{v} = \frac{8 \text{ in.} + 4.9 \text{ in.}}{0.56 \text{ in./s}} = 23.0 \text{ s}$$

8.132 A 12-in-long, 2-in-thick plate is being cut on a band saw at 150 ft/min The saw has 12 teeth per in. If the feed per tooth is 0.003 in., how long will it take to saw the plate along its length?

The workpiece speed, v, is the product of the number of teeth (12 per in.), the feed per tooth (0.003 in.), and the band saw speed (150 ft/min). The speed is thus

$$v = (12)(0.003)(150) = 5.4 \text{ ft/min} = 1.08 \text{ in./s}$$

For a 12-in. long plate, the cutting time is then (12)/(1.08)=11.1 s. Note that plate thickness has no effect on the answer.

8.133 A single-thread hob is used to cut 40 teeth on a spur gear. The cutting speed is 200 ft/min and the hob has a diameter of 4 in. Calculate the rotational speed of the spur gear.

If a single-threaded hob is used to cut forty teeth, the hob and the blank must be geared so that the hob makes forty revolutions while the blank makes one revolution. The expression for the cutting speed of the hob is

$$V = \pi DN \quad \text{or} \quad N = \frac{V}{\pi D}$$

Since the cutting speed is given as 200 ft/min = 2400 in./min, we have

$$N = \frac{V}{\pi D} = \frac{2400}{\pi(4)} = 190 \text{ rad/min} = 30.2 \text{ rpm}$$

Therefore, the rotational speed of the blank is 30.2/40 = 0.75 rpm.

8.134 In deriving Eq. (8.20) it was assumed that the friction angle, β, was independent of the shear angle, ϕ. Is this assumption valid? Explain.

We observe from Table 8.1 that the friction angle, β, and the shear angle, ϕ, are interrelated; thus, β is not independent of ϕ. Note however, that β varies at a much lower rate than ϕ does. Therefore, while it is not strictly true, the assumption can be regarded as a valid approximation.

8.135 An orthogonal cutting operation is being carried out under the following conditions: depth of cut = 0.10 mm, width of cut = 5 mm, chip thickness = 0.2 mm, cutting speed = 2 m/s, rake angle = 15°, cutting force = 500 N, and thrust force = 200 N. Calculate the percentage of the total energy that is dissipated in the shear plane during cutting.

The total power is

$$P_{\text{tot}} = F_c V = (500 \text{ N})(2 \text{ m/s}) = 1000 \text{ Nm/s}$$

The power dissipated in the shear zone is

$$P_{\text{shear}} = F_s V_s$$

where

$$F_s = R\cos(\phi + \beta - \alpha)$$

and

$$R = \sqrt{F_c^2 + F_t^2} = \sqrt{500^2 + 200^2} = 538 \text{ N}$$

Also, note that the cutting ratio is given by Eq. (8.1) on p. 420 as

$$r = \frac{t_o}{t_c} = \frac{0.10}{0.20} = 0.5$$

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From Fig. 8.2, it can be shown that

$$\begin{aligned}\phi &= \tan^{-1}\left(\frac{r\cos\alpha}{1-r\sin\alpha}\right)\\ &= \tan^{-1}\left(\frac{(0.5)\cos 15^\circ}{1-(0.5)\sin 15^\circ}\right)\\ &= 29.0^\circ\end{aligned}$$

Note that because all necessary data is given, we should not use the approximate shear-angle relationships in Section 8.2.4 to estimate the friction angle. Instead, to find β, we use Eq. (8.11):

$$F_c = R\cos(\beta-\alpha)$$

solving for β,

$$\beta = \cos^{-1}\left(\frac{F_c}{R}\right)+\alpha = \cos^{-1}\left(\frac{500}{538}\right)+15^\circ$$

or $\beta = 36.7^\circ$ Also, F_s is calculated as

$$\begin{aligned}F_s &= R\cos(\phi+\beta-\alpha)\\ &= (538\text{ N})\cos(29.0^\circ+36.7^\circ-15^\circ)\\ &= 340\text{ N}\end{aligned}$$

Also, from Eq. (8.6),

$$V_s = \frac{V\cos\alpha}{\cos(\phi-\alpha)} = \frac{(2)\cos 15^\circ}{\cos(29.0^\circ-15^\circ)}$$

or $V_s = 1.99$ m/s. Therefore,

$$P_{\text{shear}} = F_sV_s = (340\text{ N})(1.99\text{ m/s})$$

or $P_{\text{shear}} = 677$ N-m/s. Hence the percentage is 677/1000=0.678 or 67.7%. Note that this value compares well with the data in Table 8.1 on p. 430.

8.136 An orthogonal cutting operation is being carried out under the following conditions: depth of cut = 0.020 in., width of cut = 0.1 in., cutting ratio = 0.3, cutting speed = 300 ft/min, rake angle = 0°, cutting force = 200 lb, thrust force = 150 lb, workpiece density = 0.26 lb/in^3, and workpiece specific heat = 0.12 BTU/lb°F. Assume that (a) the sources of heat are the shear plane and the tool-chip interface; (b) the thermal conductivity of the tool is zero, and there is no heat loss to the environment; (c) the temperature of the chip is uniform throughout. If the temperature rise in the chip is 155°F, calculate the percentage of the energy dissipated in the shear plane that goes into the workpiece.

The power dissipated in the shear zone is given as

$$P_{\text{shear}} = F_sV_s$$

where

$$F_s = R\cos(\phi+\beta-\alpha)$$

and

$$R = \sqrt{F_c^2+F_t^2} = \sqrt{200^2+150^2} = 250\text{ lb}$$

Therefore, from Problem 8.135 above,

$$\begin{aligned}\phi &= \tan^{-1}\left(\frac{r\cos\alpha}{1-r\sin\alpha}\right)\\ &= \tan^{-1}\left(\frac{0.3\cos 0^\circ}{1-0.3\sin 0^\circ}\right)\\ &= 16.7^\circ\end{aligned}$$

Note that because all the necessary data is given, we should not use the shear-angle relationships in Section 8.2.4 to estimate the friction angle. Instead, to find β, we use Eq. (8.11) to obtain

$$F_c = R\cos(\beta-\alpha)$$

or, solving for β,

$$\begin{aligned}\beta &= \cos^{-1}\left(\frac{F_c}{R}\right)+\alpha\\ &= \cos^{-1}\left(\frac{200}{250}\right)+0^\circ\\ &= 36.9^\circ\end{aligned}$$

Therefore,

$$\begin{aligned}F_s &= R\cos(\phi+\beta-\alpha)\\ &= (250)\cos(16.7^\circ+36.9^\circ-0^\circ)\\ &= 148\text{ lb}\end{aligned}$$

Also, from Eq. (8.6),

$$V_s = \frac{V\cos\alpha}{\cos(\phi-\alpha)} = \frac{(300)\cos 0^\circ}{\cos(16.7^\circ-0^\circ)}$$

or $V_s = 313$ ft/min. Therefore,

$$P_{\text{shear}} = F_sV_s = (148)(313) = 46,350\text{ ft-lb/min}$$

or $P_{\text{shear}} = 59.6$ BTU/min. The volume rate of material removal is

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(300)(0.020)(0.10)(12)=14.4 in^3/min. Thus, the heat content, Q, of the chip is

$$\begin{aligned} Q_{\text{chip}} &= c\rho V \Delta T \\ &= (0.12 \text{ BTU/lb}^\circ\text{F}) \left(0.26 \text{ lb/in}^3\right) \\ &\quad \times \left(14.4 \text{ in}^3/\text{min}\right) (155^\circ\text{F}) \\ &= 70 \text{ BTU/min} \end{aligned}$$

The total power dissipated is

$$P_{\text{total}} = (200)(300)(1/778) = 77.1 \text{ BTU/min}.$$

Hence, the ratio of heat dissipated into the workpiece is (77.1-70)=7.1 BTU/min. In terms of the shear energy, this represents a percentage of 7.1/59.6=0.12, or 12%.

8.137 It can be shown that the angle ψ between the shear plane and the direction of maximum grain elongation (see Fig. 8.4a) is given by the expression

$$\psi = 0.5 \cot^{-1}\left(\frac{\gamma}{2}\right),$$

where γ is the shear strain, as given by Eq. (8.3). Assume that you are given a piece of the chip obtained from orthogonal cutting of an annealed metal. The rake angle and cutting speed are also given, but you have not seen the setup on which the chip was produced. Outline the procedure that you would follow to estimate the power required in producing this chip. Assume that you have access to a fully equipped laboratory and a technical library.

Remembering that we only have a piece of the chip and we do not know its relationship to the workpiece, the procedure will consist of the following steps:

(a) Referring to Fig. 8.4a on p. 422, let the angle between the direction of maximum grain elongation (grain-flow lines) and a vertical line be denoted it as η. Since we know the rake angle, we can position the chip in its proper orientation and then write

$$\phi + \gamma + \eta = 90^\circ$$

Note that we can now measure the angle η, but we still have two unknowns.

(b) From the formula given in the statement of the problem, we have a direct relationship between the angles ψ and γ. Also from Eq. (8.3) we have a relationship between ϕ and γ. Therefore, we can determine the value of γ.

(c) From an analysis of the material and its hardness, its shear stress-shear strain curve can be estimated.

(d) We can then determine the value of u_s.

(e) Since ϕ and α are known, we are now able to determine the depth of cut, t_o, and consequently, the volume rate of removal, since V and the width of cut are also known. The product of u_s and volume removal rate is the power dissipated in the shear plane.

(f) We must add to this the energy dissipated in friction, u_f, at the tool-chip interface. Based on observations such as those given in Table 8.1, we may estimate this quantity, noting that as the rake angle increases, the percentage of the friction energy to total energy increases. A conservative estimate is 50%.

8.138 A lathe is set up to machine a taper on a bar stock 120 mm in diameter; the taper is 1 mm per 10 mm. A cut is made with an initial depth of cut of 4 mm at a feed rate of 0.250 mm/rev and at a spindle speed of 150 rpm. Calculate the average metal removal rate.

For an initial depth of cut of 4 mm and a taper of 1 mm/10 mm, there will be a 40 mm length which is tapered. If the depth of cut were a constant at 4 mm, the metal removal rate would be given by Eq. (8.38) as

$$\begin{aligned} \text{MRR} &= \pi D_{\text{ave}} df N \\ &= \pi \left(\frac{120 + 116}{2}\right) (4)(0.250)(150) \\ &= 55,600 \text{ mm}^3/\text{min} \end{aligned}$$

Since the bar has a taper, the average metal removal rate is one-half this value, or 27,800 mm^3/min.

8.139 Develop an expression for optimum feed rate that minimizes the cost per piece if the tool life is as described by Eq. (8.34).

There can be several solutions for this problem, depending on the type of the machine tool. For

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example, Section 8.15 considers the case where an insert is used. The insert has a number of faces that can be used before the tool is replaced. Other tools may be used only once; others (such as drills) can be reground and reused. Since inserts are used in the textbook, the following solution considers a tool that can be periodically reground. From Eq. (8.46) on p. 507 the total cost per piece can be written as

$$C_p = C_m + C_s + C_l + C_t$$

Note that C_l and C_s will not be dependent on the feed rate. However, in turning, the machining cost can be obtained by combining Eqs. (8.47) and (8.51) to obtain

$$\begin{aligned} C_m &= T_m (L_m + B_m) \\ &= \frac{\pi LD}{fV} (L_m + B_m) \\ &= \left[\frac{\pi LD}{V} (L_m + B_m) \right] \frac{1}{f} \end{aligned}$$

The number of parts per tool grind is given as

$$N_p = \frac{T}{T_m} = \frac{C^7 V^{-7} d^{-1} f^{-4}}{\pi LD/fV} = \left(\frac{C^7}{\pi LDdV^6} \right) \frac{1}{f^3}$$

so that the tooling cost, equivalent to Eq. (8.49), is

$$C_t = \frac{1}{N_p} \left[T_c (L_m + B_m) + T_g (L_g + B_g) + D_c \right]$$

where L_g and B_g are the labor and overhead rate associated with the tool grinding operation, respectively. We can define a function Ψ as:

$$\Psi = \left[T_c (L_m + B_m) + T_g (L_g + B_g) + D_c \right]$$

which is a function of labor, overhead, and tool replacement costs, and is independent of feed. Therefore, the tooling cost is:

$$C_t = \frac{1}{N_p} \Psi = \left(\frac{\pi LDdV^6}{C^7} \right) \Psi f^3$$

The total cost per piece can be expressed as a function of feed, f:

$$\begin{aligned} C_p &= C_m + C_s + C_l + C_t + C_l + C_s \\ &= \left[\frac{\pi LD}{V} (L_m + B_m) \right] \frac{1}{f} \\ &\quad + \left(\frac{\pi LDdV^6}{C^7} \right) \Psi f^3 \end{aligned}$$

Taking the derivative with respect to the constant feed (f) and setting it equal to zero gives:

$$\begin{aligned} \frac{dC_p}{df} &= 0 \\ &= -\left[\frac{\pi LD}{V} (L_m + B_m) \right] \frac{1}{f^2} \\ &\quad + 3\Psi \left(\frac{\pi LDdV^6}{C^7} \right) f^2 \end{aligned}$$

Solving for f then gives

$$f = \left(\frac{C^7 (L_m + B_m)}{3dV^7 \Psi} \right)^{1/4}$$

8.140 Assuming that the coefficient of friction is 0.25, calculate the maximum depth of cut for turning a hard aluminum alloy on a 20-hp lathe (with a mechanical efficiency of 80%) at a width of cut of 0.25 in., rake angle of 0°, and a cutting speed of 300 ft/min. What is your estimate of the material's shear strength?

The maximum allowable cutting force that will stall the lathe is given as:

$$P = (0.8)(20 \text{ hp}) = 528,000 \text{ ft-lb/min}$$

Solving for F_c,

$$F_c = \frac{528,000 \text{ ft-lb/min}}{V} = \frac{528,000 \text{ ft-lb/min}}{300 \text{ ft/min}}$$

or $F_c = 1760$ lb. From Eq. (8.11),

$$F_c = \frac{wt_o \tau \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$

or

$$t_o = \frac{F_c \sin\phi \cos(\phi + \beta - \alpha)}{w\tau \cos(\beta - \alpha)}$$

It is known that $\alpha = 0°$ and $w = 0.25$ in. From Eq. (8.12),

$$\beta = \tan^{-1}\mu = \tan^{-1} 0.25 = 14.0°$$

Using Eq. (8.20), the shear angle, ϕ, is found as

$$\phi = 45° + \frac{\alpha}{2} - \frac{\beta}{2} = 45° + 0° - \frac{14°}{2} = 38°$$

The strength of an aluminum alloy varies widely, as can be seen from Table 3.7 on p. 116.

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Lets use $Y = 300$ MPa $= 43.5$ ksi as typical for a very hard aluminum alloy, thus the shear strength is $\tau = Y/2 = 21.7$ ksi. Hence the maximum depth of cut is

$$\begin{aligned} t_o &= \frac{F_c \sin\phi \cos(\phi + \beta - \alpha)}{w\tau \cos(\beta - \alpha)} \\ &= \frac{(1760)\sin 31^\circ \cos(31^\circ + 14^\circ - 0^\circ)}{(0.25)(21,700)\cos(14^\circ - 0^\circ)} \\ &= 0.121 \text{ in.} \end{aligned}$$

The maximum depth of cut is just under $\frac{1}{8}$ in.

8.141 Assume that, using a carbide cutting tool, you measure the temperature in a cutting operation at a speed of 250 ft/min and feed of 0.0025 in./rev as 1200°F. What would be the approximate temperature if the cutting speed is increased by 50%? What should the speed be to lower the maximum temperature to 800°F?

From Eq. (8.30) we know that

$$T \propto V^a f^b$$

or

$$T = kV^a f^b$$

where k is a constant. From Section 8.2.6, for a carbide tool, $a = 0.2$ and $b = 0.125$. For the first problem, where the cutting speed is increased by 50%, we can write

$$\frac{T_1}{T_2} = \frac{kV_1^a f_1^b}{kV_2^a f_2^b} = \frac{kV_1^a f_1^b}{k(2V_1)^a f_1^b} = \frac{1}{1.5^a} = \frac{1}{1.5^{0.2}}$$

or $\frac{T_1}{T_2} = 0.92$. Therefore, the temperature increase is 15% over the first case. Note that this equation is problematic if either of the temperatures T_1 or T_2 is zero or negative; therefore, an absolute temperature scale is required. The problem states that $T_1 = 1200$°F, thus, on an absolute scale, $T_1 = 1660$ R, and therefore, $T_2 = 1908$ R, or $T_2 = 1448$°F.

For the second problem, where $T_2 = 800$°F=1260 R, the temperature ratio is $\frac{T_1}{T_2} = 1.317$. Therefore

$$\left(\frac{V_1}{V_2}\right)^a = 1.317$$

or

$$\frac{V_1}{V_2} = (1.317)^{1/a} = 1.317^5 = 3.97$$

So that the speed has to be $250/3.97 = 63$ ft/min.

8.142 A 3-in-diameter gray cast-iron cylindrical part is to be turned on a lathe at 500 rpm. The depth of cut is 0.25 in. and a feed is 0.02 in./rev. What should be the minimum horsepower of the lathe?

The metal removal rate is given as

$$\begin{aligned} \text{MRR} &= \pi D_{\text{ave}} df N \\ &= \pi(3.875)(0.25)(0.02)(600) \\ &= 36.5 \text{ in}^3/\text{min} \end{aligned}$$

The energy requirement for cast irons is, at most, 2.0 hp.min/in^3 (see Table 8.3). Therefore, the horsepower needed in the lathe motor, corrected for 80% efficiency, is

$$P = \frac{2.0 \text{ hp-min/in}^3}{36.5 \text{ in}^3/\text{min}} = 0.05 \text{ hp}$$

This is a small number and suitable for a fractional-power lathe.

8.143 (a) A 6-in.-diameter aluminum bar with a length of 12 in. is to have its diameter reduced to 5 in. by turning. Estimate the machining time if an uncoated carbide tool is used. (b) What is the time for a TiN-coated tool?

(a) From Table 8.9 on p. 472, the range of parameters for machining aluminum with uncoated carbide tools is estimated as:

$$d = 0.01 - 0.35 \text{ in.}$$

$$f = 0.003 - 0.025 \text{ in.}$$

$$V = 650 - 2000 \text{ ft/min.}$$

This table gives a wide range of recommendations and states that coated and ceramic tools are on the high end of the recommended values. There is some variability in the actual speeds that can be selected by the student for analysis; the following solution will use these values for the uncoated carbide.

It is not advisable to produce this part in a single machining operation, since the depth of cut would exceed the recommendations given in Table 8.9. Also, as described in Section 8.9, usually one or more roughing cuts are followed by a finishing cut to meet surface finish and dimensional tolerance requirements. Since the total

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depth of cut is to be 0.5 in., it would be appropriate to perform two equal roughing cuts, each with $d = 0.24$ in., and a finishing cut at $d = 0.02$ in. For the roughing cuts, the maximum allowable feed and speed can be used, so that $f = 0.025$ in./rev and $V = 2000$ ft/min. For the finishing cuts, the feed is determined by surface finish requirements, but is assigned the minimum value of 0.003 in./rev; the speed is similarly set at a value of $V = 1000$ ft/min. The average diameter for the first roughing cut is 5.76 in., and 5.28 in. for the second cut. The rotational speeds for first and second roughing and finishing cuts are (from $V = \pi D_{\text{ave}} N$) 110 rpm, 120 rpm, and 60 rpm, respectively. The total machining time is thus

$$\begin{aligned} t &= \sum \frac{l}{fN} = \frac{12 \text{ in.}}{(0.025 \text{ in./rev})(110 \text{ rpm})} \\ &\quad + \frac{12 \text{ in.}}{(0.025 \text{ in./rev})(120 \text{ rpm})} \\ &\quad + \frac{12 \text{ in.}}{(0.02 \text{ in./rev})(60 \text{ rpm})} \\ &= 18.36 \text{ min} \end{aligned}$$

(b) For a coated tool, such as TiN, the cutting speed can be higher than the values used above. Consequently, the cutting time will be lower than that for uncoated tools.

8.144 Calculate the power required for the cases given in Problem 8.143.

Note that Problem 8.143 was an open-ended problem, and thus the specific feeds, speeds, and depths of cut depend on the number and characteristics of the roughing and finishing cuts selected. This answer will be based the solution to Problem 8.143.

For aluminum, Table 8.3 gives a specific energy of between 0.15 and 0.4 hp-min/in^3, thus a mean value of $u = 0.275$ hp-min/in^3 is chosen. Consider the first roughing cut, where $d = 0.24$ in, $f = 0.025$ in., $N = 110$ rpm, and D_{avg} is given as

$$D_{\text{avg}} = \frac{6 \text{ in.} + 5.52 \text{ in.}}{2} = 5.76 \text{ in.}$$

Therefore, the metal removal rate is given by Eq. (8.38) as:

$$\begin{aligned} \text{MRR} &= \pi D_{\text{avg}} df N \\ &= \pi(5.76)(0.24)(0.025)(110) \\ &= 11.94 \text{ in}^3/\text{min} \end{aligned}$$

Therefore, the power required is:

$$P = u(\text{MRR}) = (0.275)(11.94)$$

or $P = 3.28$ hp. Similarly, for the second roughing cut, $d = 0.24$ in, $f = 0.025$ in./rev, $N = 120$ rpm, and $D_{avg} = 5.28$ in. Therefore, MRR=11.94 in^3/min and $P = 3.28$ hp. For the finishing cut, $d = 0.01$ in., $f = 0.02$ in/rev, $N = 60$ rpm and $D_{\text{avg}} = 5.01$ in. Therefore, MRR=0.19 in^3/min and $P = 0.052$ hp.

8.145 Using trigonometric relationships, derive an expression for the ratio of shear energy to frictional energy in orthogonal cutting, in terms of angles α, β, and ϕ only.

We begin with the following expressions for u_s and u_f, respectively, (see Section 8.2.5):

$$u_s = \frac{F_s V_s}{w t_o V} \quad \text{and} \quad u_f = \frac{F V_c}{w t_o V}$$

Thus, their ratio becomes

$$\frac{u_s}{u_f} = \frac{F_s V_s}{F V_c}$$

The terms involved above can be defined as

$$F = R \sin \beta$$

and from Fig. 8.11,

$$F_s = R \cos(\phi + \beta - \alpha)$$

However, this expression can be simplified further by noting in the table for Problem 8.107 that the magnitudes of ϕ and α are close to each other. This expression can thus be approximated as

$$F_s = R \cos \beta$$

Also,

$$V_s = \frac{V \cos \alpha}{\cos(\phi - \alpha)}$$

$$V_c = \frac{V \sin \alpha}{\cos(\phi - \alpha)}$$

Combining these expressions and simplifying, we obtain

$$\frac{u_s}{u_f} = \cot \beta \cot \alpha$$

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8.146 For a turning operation using a ceramic cutting tool, if the cutting speed is increased by 50%, by what factor must the feed rate be modified to obtain a constant tool life? Let $n = 0.5$ and $y = 0.6$.

Equation (8.33) will be used for this problem. Since the tool life is constant, we can write the following:

$$\frac{C^{1/n} d_1^{-x/n} f_1^{-y/n}}{V_1^{1/n}} = \frac{C^{1/n} d_2^{-x/n} f_2^{-y/n}}{V_2^{1/n}}$$

Note that the depth of cut is constant, hence $d_1 = d_2$, and also it is given that $V_2 = 1.5V_1$. Substituting the known values into this equation yields:

$$V_1^{-2} f_1^{-0.6/0.5} = (1.5V_1)^{-2} f_2^{-0.6/0.5}$$

or

$$1.5^2 = \left(\frac{f_1}{f_2}\right)^{-1.2}$$

so that

$$\frac{f_1}{f_2} = \left(1.5^2\right)^{1/1.2} = 1.96$$

or the feed has to be reduced by about 50%.

8.147 Using Eq. (8.35), select an appropriate feed for $R = 1$ mm and a desired roughness of 1 μm. How would you adjust this feed to allow for nose wear of the tool during extended cuts? Explain your reasoning.

If $R_a = 1$ μm, and $R = 1$ mm, then

$$f^2 = (1\ \mu\text{m})(8)(1\ \text{mm}) = 8 \times 10^{-9}\ \text{m}^2$$

Therefore,

$$f = 0.089\ \text{mm/rev}$$

If nose wear occurs, the radius will increase. The feed will similarly have to increase, per the equation above.

8.148 In a drilling operation, a 0.5-in. drill bit is being used in a low-carbon steel workpiece. The hole is a blind hole which will then be tapped to a depth of 1 in. The drilling operation takes place with a feed of 0.010 in./rev and a spindle speed of 700 rpm. Estimate the time required to drill the hole prior to tapping.

The velocity of the drill into the workpiece is $v = fN = (0.010\ \text{in./rev})(700\ \text{rpm}) = 7$ in./min. Since the hole is to be tapped to a depth of 1 in., it should be drilled deeper than this distance. Note from Section 8.9.4 that the point angle for steels ranges from 118° to 135°, so that (using 118° to get a larger number and conservative answer) the drill actually has to penetrate at least a distance of

$$\begin{aligned} l &= 1 + \frac{d}{2}\sin(90^\circ - 118^\circ/2) \\ &= 1 + \left(\frac{0.5\ \text{in.}}{2}\right)(\sin 31^\circ) \\ &= 1.13\ \text{in.} \end{aligned}$$

In order to ensure that the tap doesn't strike the bottom of the hole, let's specify that the drill should penetrate 1.25 in., which is the nearest 1/4 in. over the minimum depth of the hole. Therefore, the time required for this drilling operation is 1.25 in./(7 in./min) = 0.18 min = 11 s.

8.149 Assume that in the face-milling operation shown in Fig. 8.54, the workpiece dimensions are 5 in. by 10 in. The cutter is 6 in. in diameter, has 8 teeth, and rotates at 300 rpm. The depth of cut is 0.125 in. and the feed is 0.005 in./tooth. Assume that the specific energy required for this material is 2 hp-min/in^3 and that only 75% of the cutter diameter is engaged during cutting. Calculate (a) the power required and (b) the material removal rate.

From the information given, the material removal rate is

$$\begin{aligned} \text{MRR} &= (0.005\ \text{in./tooth})(8\ \text{teeth/rev}) \\ &\quad \times (300\ \text{rev/min})(0.125\ \text{in.}) \\ &\quad \times (0.75)(6\ \text{in.}) \end{aligned}$$

or MRR = 6.75 in^3/min. Since the specific energy of material removal is given as 2 hp-min/in^3,

$$\text{Power} = (6.75)(2) = 13.5\ \text{hp}$$

8.150 Calculate the ranges of typical machining times for face milling a 10-in.-long, 2-in.-wide cutter and at a depth of cut of 0.1 in. for the following workpiece materials: (a) low-carbon steel, (b) titanium alloys, (c) aluminum alloys, and (d) thermoplastics.

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The cutting time, t, in face milling is by Eq. (8.44) as

$$t = \frac{l + l_c}{v}$$

We know that $l = 10$ in., hence, as calculated in Example 24.1 (and proven in Problem 24.36), l_c is obtained as

$$l_c = \sqrt{Dd} = \sqrt{(2 \text{ in.})(0.1 \text{ in.})} = 0.45 \text{ in.}$$

The remaining main variable is the feed, a range of which can be seen in Table 8.12 for the materials listed in the problem. For example, with low-carbon steel, the feed per tooth is 0.003-0.015 in/tooth. The cutting time, as obtained for 10 teeth in the cutter. is given below:

Material	Maximum time (s)	Minimum time (s)
Low-carbon steel	348	70
Titanium alloys	348	70
Aluminum alloys	348	58
Thermoplastics	348	58

8.151 A machining-center spindle and tool extend 12 in. from its machine-tool frame. What temperature change can be tolerated to maintain a tolerance of 0.0001 in. in machining? A tolerance of 0.001 in.? Assume that the spindle is made of steel.

The extension due to a change in temperature is given by

$$\Delta L = \alpha \Delta T L$$

where α is the coefficient of thermal expansion, which, for carbon steels, is $\alpha = 6.5 \times 10^{-6}/°\text{F}$. If $\Delta L = 0.0001$ in. and $L = 12$ in., then ΔT can easily be calculated to be 1.28°F. Also, for $\Delta L = 0.001$ in., we have $\Delta T = 12.8°\text{F}$. Noting that the temperatures involved are quite small, this example clearly illustrates the importance of environmental control in precision manufacturing operations, where dimensional tolerances are extremely small.

8.152 In the production of a machined valve, the labor rate is \$19.00 per hour and the general overhead rate is \$15.00 per hour. The tool is a square ceramic insert and costs \$25.00; it takes five minutes to change and one minute to index. Estimate the optimum cutting speed from a cost perspective. Let $C = 100$ for V_o in m/min.

The optimum cutting speed is given by Eq. (8.57) as:

$$V_o = \frac{C\,(L_m + B_m)^n}{\left(\frac{1}{n} - 1\right)^n \Psi^n}$$

where

$$\Psi = \frac{1}{m}\left[T_c\,(L_m + B_m) + D_i\right] + T_i(L_m + B_m)$$

Note that for a ceramic tool, n is estimated from Table 8.4 as 0.50. For L_m = \$19.00, B_m = \$15.00, $m = 4$, D_i = \$25.00, $T_c = 5$ min, and $T_i = 1$ min,

$$\Psi = \frac{1}{4}\left[\frac{5}{60}(19 + 15) + 25\right] + 1(19 + 15)$$

or $\Psi = 40.95$. Therefore, the optimum cutting speed is

$$\begin{aligned} V_o &= \frac{C\,(L_m + B_m)^n}{\left(\frac{1}{n} - 1\right)^n \Psi^n} \\ &= \frac{(100)\,(19 + 15)^{0.5}}{\left(\frac{1}{0.5} - 1\right)^{0.5} 7.525^{0.5}} \\ &= 91 \text{ m/min.} \end{aligned}$$

8.153 Estimate the optimum cutting speed in Problem 8.152 for maximum production.

Using the same values as in Problem 8.152, the optimum cutting speed for maximum production is determined from Eq. (8.60) as:

$$V_o = \frac{C}{\left[\left(\frac{1}{n} - 1\right)\left(\frac{T_c}{m} + T_i\right)\right]^n}$$

Substituting appropriate values, this gives a cutting speed of 66.67 m/min for the ceramic inserts.

8.154 Develop an equation for optimum cutting speed in a face milling operation using a milling cutter with inserts.

The analysis is similar to that for a turning operation presented in Section 8.15. Note that some minor deviations from this analysis should be acceptable, depending on the specific assumptions made. The general approach should, however, be consistent with the following solution.

The main differences between this problem and that in Section 8.15 are

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(a) The tool cost is given by:

$$C_t = \frac{1}{N_p}\left[T_c\left(L_m + B_m\right) + D_c + T_i\left(L_m + B_m\right)\right]$$

where N_p = number of parts produced per tool change, T_i=time required to change inserts, D_c is the cost of the inserts, and remaining terminology is consistent with that in the textbook.

(b) If the approach distance, l_c, can be ignored, the machining time is obtained from Eqs. (8.43) and (8.44) as

$$T_m = \frac{lD}{fVm}$$

where l is the cutting length, D is the cutter diameter, f is the feed per tooth, m is the number of teeth on the cutter periphery and C is the cutting speed. Note that m is the variable used to represent the number of inserts, whereas n is used in Eq. (8.43). This substitution of variables has been made to avoid confusion with the exponent in the Taylor tool life equation. Note that this equation for cutting time is only slightly different than Eq. (8.51).

Also note that the Taylor tool life equation results in:

$$T = \left(\frac{C}{V}\right)^{1/n}$$

so that the number of parts per tool change is:

$$N_p = \frac{T}{T_m} = \frac{C^{1/n} f V^{(n-1)/n} m}{lD}$$

Substituting into Eq. (8.46),

$$C_p = V^{-1}\frac{lD}{fm}\left(L_m + B_m\right) + C_s + C_l + \frac{lD}{C^{1/n} fm} V^{n/(n-1)}\Psi$$

where

$$\Psi = T_c\left(L_m + B_m\right) + D_c + T_i\left(L_m + B_m\right)$$

Taking the derivative with respect to V:

$$\frac{dC_p}{dV} = 0 = -V^{-2}\frac{lD(L_m + B_m)}{fm} + \frac{n}{n-1}\frac{lD}{C^{1/n} fm}\Psi V^{n/(n-1)-1}$$

Solving for V,

$$\frac{V^{-2}}{V^{1/(n-1)}} = \frac{\frac{n}{n-1}\frac{lD}{C^{1/n} fm}\Psi}{\frac{lD(L_m + B_m)}{fm}}$$

simplifying,

$$V = \left(\frac{\frac{n}{n-1} C^{-1/n}\Psi}{L_m + B_m}\right)^{\frac{n-1}{2n-3}}$$

8.155 Develop an equation for optimum cutting speed in turning where the tool is a high speed steel tool that can be reground periodically.

Compared to Section 8.15, the main difference is in the equation for C_t. Thus, Eq. (8.49) becomes

$$C_t = \frac{1}{N_p}\left[T_c\left(L_m + B_m\right) + T_g\left(L_g + B_g\right) + D_c\right]$$

or, in order to simplify,

$$C_t = \frac{\Psi}{N_p}$$

Note that Ψ is independent of cutting and thus can be assumed to be constant in this derivation. Just as done in Section 8.15, these relations are substituted into the cost per piece given by Eq. (8.46), the derivative with respect to V is taken and set equal to zero. The result is

$$V_o = \frac{C(L_m + B_m)^n}{\left[\left(\frac{1}{n} - 1\right)\Psi\right]^n}$$

If we substitute for Ψ, this is an expression very similar to Eq. (8.57).

8.156 Assume that you are an instructor covering the topics in this chapter, and you are giving a quiz on the quantitative aspects to test the understanding of the students. Prepare several numerical problems, and supply the answers to them.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

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Design

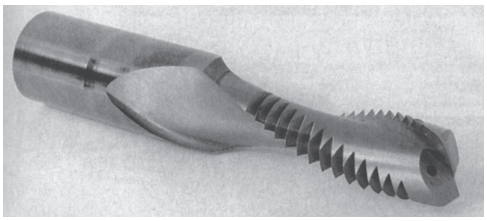
8.157 Tool life could be greatly increased if an effective means of cooling and lubrication were developed. Design methods of delivering a cutting fluid to the cutting zone and discuss the advantages and shortcomings of your design.

By the student. This is an open-ended problem and students are encouraged to pursue creative solutions. Methods of delivering fluid to the cutting zone include (see also Section 8.7.1):

(a) Flooding or mist cooling of the cutting zone, which has been the traditional approach.

(b) High-pressure coolant application.

(c) Using a tool with a central hole or other passageway to allow for the fluid to be pumped into the cutting zone; an example is the end mill shown below.



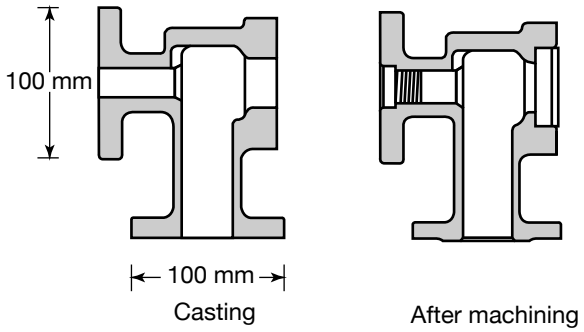
8.158 Devise an experimental setup whereby you can perform an orthogonal cutting operation on a lathe using a short round tubular workpiece.

By the student. This can be done simply by placing a thin-walled tube in the headstock of a lathe (see Fig. 8.19, where the solid bar is now replaced with a tube) and machining the end of the tube with a simple, straight tool (as if to shorten the length of the tube). Note that the feed on the lathe will become the depth of cut, t_o, in orthogonal cutting, and the chip width will be the same as the wall thickness of the tube.

8.159 Cutting tools are sometimes designed so that the chip-tool contact length is controlled by recessing the rake face some distance away from the tool tip (see the leftmost design in Fig. 8.7c). Explain the possible advantages of such a tool.

By the student. The principal reason is that by reducing the tool-chip contact, the friction force, F, is reduced, thus friction and cutting forces are reduced. Chip morphology may also change. The student is encouraged to search the technical literature regarding this topic.

8.160 The accompanying illustration shows drawings for a cast-steel valve body before (left) and after (right) machining. Identify the surfaces that are to be machined (noting that not all surfaces are to be machined). . What type of machine tool would be suitable to machine this part? What type of machining operations are involved, and what should be the sequence of these operations?



By the student. Note that the dimensions of the part suggest that most of these surfaces are produced in a drill press, although a milling machine could also be used. However, the sharp radius in the enlarged hole on the right side cannot be produced with a drill; this hole was bored on a lathe.

8.161 Make a comprehensive table of the process capabilities of the machining operations described in this chapter. Use several columns describe the (a) machines involved, (b) type of tools and tool materials used, (c) shapes of blanks and parts produced, (d) typical maximum and minimum sizes produced, (e) surface finish produced, (f) dimensional tolerances produced, and (g) production rates achieved.

By the student. This is a challenging and comprehensive problem with many possible solutions. Some examples of acceptable answers would be:

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Process	Machine tools	Cutting-tool materials	Shapes	Typical sizes
Turning	Lathe	Assorted; see Table 23.4	Axisymmetric	1-12 in. diameter, 4-48 in. length
Drilling	Lathe, mill drill press	Assorted, usually HSS	Circular holes	1-100 mm (50 μm possible)
Knurling	Lathe, mill	Assorted, usually HSS	Rough surfaces on axisymmetric parts	Same as in turning

8.162 A large bolt is to be produced from hexagonal bar stock by placing the hex stock into a chuck and machining the cylindrical shank of the bolt by turning on a lathe. List and explain the difficulties that may be involved in this operation.

By the student. There could several difficulties with this operation. Obviously the process involves interrupted cutting, with repeated impact between the cutting-tool and the workpiece surface, and the associated dynamic stresses which, in turn, could lead to tool chipping and breakage. Even if the tool survives, chatter may be unavoidable in the early stages (depending on the characteristics of the machine-tool and of the fixtures used) when the depth of cut variations are at their maximum. Note that the ratio of length-to-cross-sectional area of the bolt also will have an influence on possible vibration and chatter.

8.163 Design appropriate fixtures and describe the machining operations required to produce the piston shown in Fig. 12.62.

By the student. Note that the piston has to be turned on a lathe to establish the exterior surface and the grooves for the piston rings, and can be fixtured on an internal surface for these operations. The seat for the main piston bearing requires end milling and boring, and can be fixtured on its external surface. The face of the piston needs contour milling because of the close tolerances with the cylinder head.

8.164 In Figs. 8.16 and 8.17b, we note that the maximum temperature is about halfway up the face of the tool. We have also described the adverse effects of temperature on various tool materials. Considering the mechanics of cutting operations, describe your thoughts on the technical and economic merits of embedding a small insert, made of materials such as ceramic or carbide, halfway up the rake face of a tool made of a material with lower resistance to temperature than ceramic or carbide.

By the student. This is an interesting problem that has served well as a topic of classroom discussion. The merits of this suggestion include:

(a) If performed properly, the tool life could be greatly improved, and thus the economics of the cutting operation could be greatly affected in a favorable way.

(b) Brazing or welding an insert is probably easier than applying a coating at an appropriate location.

The drawbacks of this approach include:

(a) The strength of the joint between insert and tool material must be high in order to withstand machining operation.

(b) It is likely that the tool will wear beyond where the insert is placed.

(c) Thermal stresses can develop, especially at the interface where coefficients of thermal expansion may be significantly different.

8.165 Describe your thought on whether chips produced during machining can be used to make useful products. Give some examples of possible products and comment on their characteristics and differences as compared to the same products made by other manufacturing processes. Which types of chips would be desirable for this purpose? Explain.

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By the student. This is an interesting design project and represents an example of cradle-to-cradle life-cycle design (see Section 1.4). Some examples of possible applications include:

(a) If the chips are discontinuous, they can have a high aspect ratio transverse to the cutting direction; these chips can then serve as metal reinforcement in composite materials.

(b) Filters can be made by compacting metal chips into suitable shapes, such as cylindrical or tubular.

(c) The chips can be used as a vibration-isolating elastic support.

(d) The chips can be further conditioned (such as in a ball mill) to produce different forms or powders.

(e) The chips can be used as a precursor in chemical vapor deposition.

(f) Numerous artwork can be developed for unique chips.

8.166 Experiments have shown that it is possible to produce thin, wide chips, such as 0.08 mm (0.003 in.) thick and 10 mm (4 in.) wide, which would be similar to rolled sheet. Materials used have been aluminum, magnesium, and stainless steel. A typical setup would be similar to orthogonal cutting, by machining the periphery of a solid round bar with a straight tool moving radially inward (plunge). Describe your thoughts on producing thin metal sheet by this method, its surface characteristics, and its properties.

By the student. This is an interesting problem that has served well as a topic of classroom conversation. This process does not appear to be in any way advantageous to metal rolling. However, many aerospace alloys are too brittle or hard to be rolled economically, and this method offers a possible manufacturing approach. This technique has also been used to develop materials that are highly oriented, which, for example, can, for example, positively influence magnetic. Note from Figs. 8.2 and 8.5 that the sheet would have a smooth surface on one side (where it has rubbed against the tool face) and a rough surface on the opposite side.

8.167 One of the principal concerns with coolants is degradation due to biological attack by bacteria. To prolong their life, chemical biocides are often added, but these biocides greatly complicate the disposal of coolants. Conduct a literature search regarding the latest developments in the use of environmentally-benign biocides in cutting fluids.

By the student. This is an interesting topic for a research paper. New and environmentally benign biocides are continuously being developed, with some surprising requirements. For example, the economic and safety and ecological concerns are straightforward. However, there is also the need to consider factors such as the taste of the biocide. That is, if a food container is produced, trace amounts of lubricant and biocide will remain on the surface and can influence the taste of the contents. Note that these traces are not considered hazardous. Also, the repeatability of the biocide is an issue; it must be controllable to fulfill TQM considerations (see Section 4.9).

8.168 If expanded honeycomb panels (see Section 7.5.5) were to be machined in a form milling operation (see Fig.8.58b), what precautions would you take to keep the sheet metal from buckling due to cutting forces? Think of as many solutions as you can.

By the student. This is an open-ended problem can be interpreted in two ways: That the honeycomb itself is being pocket machined, or that a fabricated honeycomb is being contoured. Either problem is a good opportunity to challenge students to develop creative solutions. Acceptable approaches include:

(a) high-speed machining, with properly chosen processing variables,

(b) using alternative processes, such as chemical machining,

(c) filling the cavities of the honeycomb structure with a low-melting-point metal (to provide strength to the thin layers of material being machined) which is then melted away after the machining operation has been completed, and

(d) filling the cavities with wax, or with water

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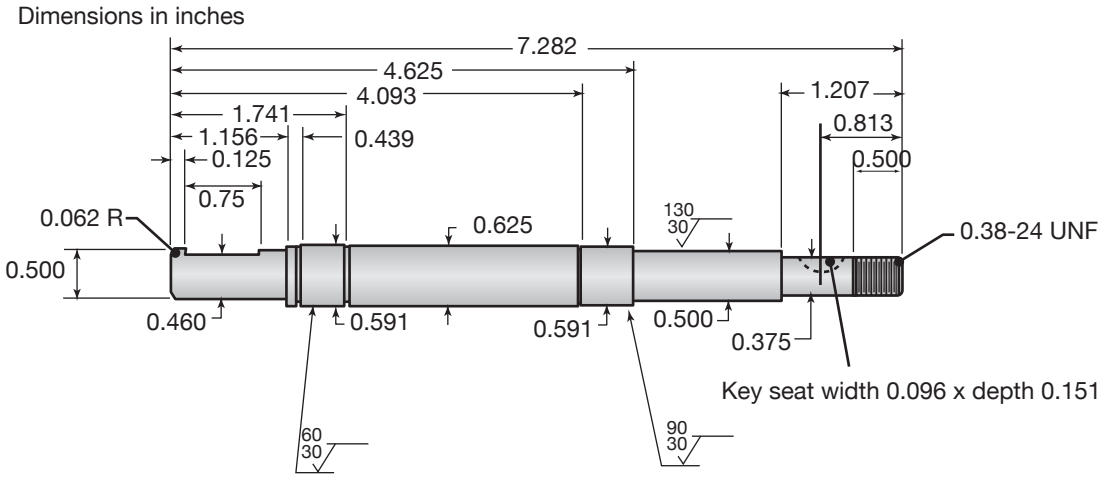
(which is then frozen), and melted after the machining operation is completed.

8.169 The part shown in the accompanying figure is a power-transmitting shaft; it is to be produced on a lathe. List the operations that are appropriate to make this part and estimate the machining time.



By the student. Note that the operations should be designed to incorporate, as appropriate, roughing and finishing cuts and should minimize the need for tool changes or refixturing.

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Chapter 9

Material-Removal Processes: Abrasive, Chemical, Electrical, and High-Energy Beams

Questions

9.1 Why are grinding operations necessary for parts that have been machined by other processes?

The grinding operations are necessary for several reasons, as stated in Section 9.1. For example, the hardness and strength of the workpiece may be too high to be machined to final dimensions economically; a better surface finish and dimensional tolerance is needed; or the workpiece is too slender to support machining forces. Students are encouraged to expand on these statements, giving specific examples based on the contents of Chapters 8 and 9.

9.2 Explain why there are so many different types and sizes of grinding wheels.

There numerous types and sizes of grinding wheels because of the different types of operations performed on a variety of materials. The geometry of a grinding wheel and the material and structural considerations for a grinding wheel depend upon the workpiece shape and characteristics, surface finish desired, production rate, heat generation during the process, economics of wheel wear, and type of grinding fluids used.

9.3 Why are there large differences between the specific energies involved in grinding (Table 9.3) and in machining (Table 8.3)? Explain.

Specific energies in grinding, as compared to machining, are much higher (see Table 9.3 on p. 534) due to:

(a) The presence of wear flats, causing high friction.

(b) The large negative rake angles of the abrasive grains, whereby the chips formed during grinding undergo higher deformation, and thus require more energy.

(c) Size effect, due to very small chips produced (see Example 9.1 on p. 532), has also been discussed as a contributing factor.

9.4 Describe the advantages of superabrasives over conventional abrasives.

By the student. See also Sections 8.6.7 and 8.6.9. Superabrasives are extremely hard (diamond and cubic boron nitride are the two hardest materials known), thus they are able to remove material even from the hardest workpiece. Their higher costs are an important economic consideration.

9.5 Give examples of applications for the grinding wheels shown in Fig. 9.2.

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By the student; see also the Bibliography at the end of the chapter. As an example, the flaring cup wheel shown in Fig. 9.2d is commonly used for surface grinding with hand-held grinders, and the mounted wheel shown in Fig 9.2g is a common wheel for manual rework of dies.

9.6 Explain why the same grinding wheel may act soft or hard.

An individual grinding wheel can act soft or hard depending on the particular grinding conditions. The greater the force on the grinding wheel grains, the softer the wheel acts; thus, a grinding wheel will act softer as the workpiece material strength, work speed, and depth of cut increase. It will act harder as the wheel speed and wheel diameter increase. Equation (9.6) gives the relationship between grain force and the process parameters. See also Section 9.5.2.

9.7 Describe your understanding of the role of friability of abrasive grains on the performance of grinding wheels.

By the student. High friability means that the grains will fracture with relative ease during grinding. In effect, this allows for sharp cutting points to be developed, leading to more effective grinding. If, on the other hand, the grains do not fracture easily, the cutting points will become dull and grinding will become inefficient; this situation will then lead to unacceptable temperature rise and adversely affecting surface integrity.

9.8 Explain the factors involved in selecting the appropriate type of abrasive for a particular grinding operation.

By the student. Consider, for example, the following: Abrasives should be inert to the workpiece material so that the material does not bond to the abrasive grain during the grinding operation, as this will reduce the effectiveness of the abrasive. The abrasives should be of appropriate size for the particular application. Applications that require better surface finish require smaller grains, while those where surface finish is a secondary consideration to removal rate should use larger grains. The grinding wheel should provide for heat removal from the cutting zone, either through the chips generated or the use of grinding fluids.

9.9 What are the effects of wear flat on the grinding operation? Are there similarities with the effects of flank wear in metal cutting? Explain.

A wear flat causes dissipation of energy and increases the temperature of the operation through friction. Wear flats are undesirable because they provide no useful work (they play no obvious role in producing the chip) but they significantly increase the frictional forces and can cause severe temperature rise of the workpiece. Recall that in orthogonal cutting, flank wear is equivalent to wear flats in grinding (see, for example, Fig. 8.20a on p. 440).

9.10 It was stated that the grinding ratio, G, depends on the following factors: (1) type of grinding wheel, (2) workpiece hardness, (3) wheel depth of cut, (4) wheel and workpiece speeds, and (5) type of grinding fluid. Explain why.

The grinding ratio, G, decreases as the grain force increases and is associated with high attritious wear of the wheel. Consider also:

(a) The type of wheel will have an effect on wheel wear; vitrified wheels generally wear slower than resinoid bonded.

(b) Depth of cut has a similar effect.

(c) Workpiece hardness will lower G because of increased wear, if all other process parameters are kept constant.

(d) Wheel and workpiece speed affect wear in opposite ways; higher wheel speed reduces the force on the grains, which reduces wheel wear.

(e) Type of grinding fluid, as it reduces wear and thus improves the efficiency of grinding.

9.11 List and explain the precautions you would take when grinding with high precision. Comment on the role of the machine, process parameters, the grinding wheel, and grinding fluids.

By the student. When grinding for high precision (see also p. 477), it is essential that the forces involved remain low so that workpiece and machine deflections are minimal. As can

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be seen from Eq. (9.6) on p. 532, to minimize grinding forces, hence minimize deflections, the wheel speed should preferably be high, the workpiece speed should be low, and the depth of cut should be small. The machine used should have high stiffness with good bearings. The temperature rise, as given by Eq. (9.9) on p. 535, should be minimized.

The grinding wheel should have fine grains and the abrasive should be inert to the workpiece material to avoid any adverse reactions. A grinding fluid should be selected to provide low wheel loading and wear, and also to provide for effective cooling. Automatic dressing capabilities should be included and the wheel should be dressed often.

9.12 Describe the methods you would use to determine the number of active cutting points per unit surface area on the periphery of a straight (Type 1; see Fig. 9.2a) grinding wheel. What is the significance of this number?

By the student. One method is to examine the wheel periphery under a microscope, and count the points that are in sharp focus. Another method is to measure the chip thickness and other variables in a known grinding operation and use Eq. (9.5) on p. 532 to determine C. Another method involves rolling the grinding wheel over a flat glass coated with soot; each point on the periphery of the wheel contacting the soot removes a small amount of soot. The glass is then placed under a microscope and with back lighting, the points are counted and expressed as a number per unit area. Note, however, soot thickness will affect the results.

9.13 Describe and explain the difficulties involved in grinding parts made of (a) thermoplastics, (b) thermosets, and (c) ceramics.

By the student. Some of the difficulties encountered would be:

(a) Thermoplastics have a low melting point and have a tendency to soften and become gummy; thus, they tend to bond to grinding wheels by mechanical locking. An effective coolant, including cool air jet, can be used to keep temperatures low.

(b) The low elastic modulus of thermoplastics can make it difficult to hold dimensional tolerances during grinding.

(c) Thermosets are harder and do not soften with temperature (although they decompose and crumble at high temperatures). Consequently, grinding by using appropriate wheels and processing parameters is relatively easy.

(d) Grinding of ceramics is relatively easy by using diamond wheels, appropriate processing parameters, and implementing ductile-regime grinding. Note also the availability of machinable ceramics (see p. 702).

9.14 Explain why ultrasonic machining is not suitable for soft and ductile metals.

In ultrasonic machining, the stresses developed from particle impact should be sufficiently high to cause spalling of the workpiece. This involves surface fracture on a very small scale. If the workpiece is soft and ductile, the impact force will simply deform the workpiece locally (as does the indenter in a hardness test), instead of causing fracture.

9.15 It is generally recommended that a soft-grade wheel be used for grinding hardened steels. Explain why.

Note that grinding hardened steels involves higher forces and the use of hard-grade wheels (meaning higher bond strength; see Section 9.3.2) will tend to cause wear and dulling of the abrasive grains. As a result, temperature will increase, possibly causing surface damage and loss of dimensional accuracy. The use of a soft-grade wheel (see Figs. 9.4 and 9.5) means that under the high grinding forces present, dull grains will be dislodged more easily, exposing sharp new cutting edges and thus leading to more efficient grinding.

9.16 Explain the reasons that the processes described in this chapter may adversely affect the fatigue strength of materials.

Fatigue (see Section 2.7) is a complex phenomenon which accounts for a vast majority of component failures. It is known that cracks

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generally start at or just below the workpiece surface, and grow with repeated cyclic loadings. Since different material-removal processes result in different surface finishes (see, for example, Fig. 8.26 on p. 448), the size and shape of cracks, and also similar stress raisers, vary with the particular process employed. This is the basic reason why smooth polished surfaces are best suited for fatigue applications. Recall also the role of residual stresses, particularly the beneficial effects of compressive surface residual stresses, in improving the fatigue strength of materials.

9.17 Describe the factors that may cause chatter in grinding operations and give the reasons why they cause chatter.

Grinding chatter (see Section 9.6.8) is similar to chatter in machining, hence many of the factors discussed in Section 8.12 apply here as well. Basically, chatter is caused by any periodic variation in grinding forces. Factors that contribute to chatter are: stiffness of the machine and damping of vibration, irregular grinding wheels, improper dressing techniques, uneven wheel wear, high material-removal rates, eccentric support or mounting of wheels, gears and shafts, vibrations from nearby machines through foundations, and inadequate clamping of the workpiece. Sources of regenerative chatter, such as workpiece material inhomogeneity and surface irregularities (such as from a previous machining operation), also can cause chatter.

9.18 Outline the methods that are generally available for deburring manufactured parts. Discuss the advantages and limitations of each method.

By the student. See Section 9.8. Some examples of methods for deburring include grinding using bench or hand grinders, using wire brushes, filing, scraping, chemical machining, and tumbling in a ball mill.

9.19 In which of the processes described in this chapter are the physical properties of the workpiece material important? Explain.

By the student. Recall that advances machining processes generally depend on the electrical and chemical properties of the workpiece material. Thus, for example, hardness, which is an important factor in conventional machining processes, is not significant in chemical machining because it does not adversely affect the ability of the chemical to react with the workpiece. The student should elaborate further based on the contents of this chapter.

9.20 Give all possible technical and economic reasons that the material removal processes described in this chapter may be preferred, or even required, over those described in Chapter 8.

By the student. Note that the main reasons are listed in Section 9.1. Students are encouraged to give specific examples after studying each of the individual processes.

9.21 What processes would you recommend for die sinking in a die block, such as that used for forging? Explain. (See also Section 6.7.)

By the student. Review the die manufacturing methods described in Section 6.7, and note that the most commonly used die-sinking methods are:

(a) milling, using rounded-tip end mills, followed by finishing processes, including grinding and polishing, and

(b) electrical-discharge machining.

1. smaller dies may be made by processes such as electrochemical machining and hubbing.

9.22 The proper grinding surfaces for each type of wheel are shown in Fig. 9.2. Explain why grinding on other surfaces of the wheel is improper and/or unsafe.

Because the wheels are designed to resist grinding forces, the proper grinding faces indicated in Fig. 9.2 on p. 507 should be utilized. Note, for example, that if grinding forces act normal to the plane of a thin straight wheel (Type 1), the wheel will flex and may eventually fracture. Thus, from a functional standpoint, grinding wheels are made stiffer in the directions in which they are intended to be used. There are serious safety and functional considerations involved. For example, an operator grinding on the side surface of a flared-cup wheel causes

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wear to take place. The flange thickness is then significantly reduced and the wheel may eventually fracture, exploding with violent force and potentially causing serious injury or death.

9.23 Note that wheel (b) in Fig. 9.3 has serrations along its periphery. Explain the reason for such a design.

The basic advantages of this design are the following:

(a) The stresses developed (rotational as well as thermal) along the periphery of the wheel are lower.

(b) The serrations allow increased flow of grinding fluid, thus lowering temperatures and reducing wheel wear,

(c) The grinding chips can be ejected easier from the grinding zone through these grooves.

9.24 In Fig. 9.10, it will be noted that wheel speed and grinding fluids can have a major effect on the type and magnitude of residual stresses developed in grinding. Explain the possible reasons for these phenomena.

Grinding wheel speed affects temperature in the same way that cutting-tool speed affects temperature (see Section 8.2.6), but the effect is more complex and even greater in grinding since a significant portion of the energy is dissipated in plowing and sliding abrasive grains over the workpiece surface without chip generation (see Figs. 9.7 and 9.9). The three grinding fluids indicated in the figure have different effectiveness on grinding mechanics and thus in reducing the temperature, leading to lower residual stresses. This is a good topic for a student paper.

9.25 Explain the consequences of allowing the workpiece temperature to rise excessively in grinding operations.

Recall the discussion of residual stresses in the answer to Question 9.24. Temperature rise can have additional major effects in grinding, including:

(a) If excessive, it can cause metallurgical burn and heat checking.

(b) The workpiece may distort due to thermal gradients.

(c) With increasing temperature, the part will expand, and thus the actual depth of cut will be greater. Upon cooling, the part will contract and the dimensional tolerances may not be within the desired range.

9.26 Comment on any observations you have regarding the contents of Table 9.4.

By the student. Students should be encouraged to make comparisons and list advantages and disadvantages of the processes listed in the table. An instructor may ask students to answer this question for a particular workpiece material, such as carbon steel, Ti-6Al-4V, or a hard ceramic, or to calculate the grinding time to produce a simple part.

9.27 Why has creep-feed grinding become an important manufacturing process? Explain.

Recall that the advantages of creep-feed grinding (see Section 9.6.6) is the ability for high material-removal rates while still maintaining the advantages in high dimensional tolerance and surface finish of grinding operations, and thus significant economic advantages. Note that these advantages are most pronounced with highly-alloyed materials which are difficult to machine, and where an abrasive process is required.

9.28 There has been a trend in manufacturing industries to increase the spindle speed of grinding wheels. Explain the possible advantages and limitations of such an increase in speed.

Increasing spindle speed has the benefit of increasing the material-removal rate, thus increasing productivity and reducing costs; see also high-speed machining, Section 8.8. The drawbacks could include increases in temperatures [see Eq. (9.9) on p. 535] and associated problems, and more importantly the need for more stiff machine tools and better bearings to avoid chatter. Also, grinding wheels, if improperly designed, manufactured, selected, used, or handled, can explode at high spindle speeds.

9.29 Why is preshaping or premachining of parts generally desirable in the advanced machining processes described in this chapter? Explain.

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By the student. This is basically a matter of economics, since large amounts of material may first be removed by other means in less time and at lower cost. Surface finish and dimensional accuracy is not important in these preshaping operations, unless they cause serious substrate damage that cannot be removed by subsequent material removal and finishing processes.

9.30 Why are finishing operations sometimes necessary? How could they be minimized to reduce product costs? Explain, with examples.

By the student. Finishing operations are necessary when the dimensional tolerances or surface finish required cannot be obtained from primary processing. For example, sand casting cannot produce a very smooth surface finish whereas grinding can. However, if the part could be roll forged instead of cast, smooth surfaces can be obtained. The trend towards near-net-shape manufacturing (see p. 18) is driven by a desire to avoid time-consuming and costly finishing operations.

9.31 Why has the wire-EDM process become so widely used in industry, especially in tool and die manufacturing? Explain.

Wire EDM has become widely accepted for several reasons (see also Section 9.13.2). The process is relatively easy to automate, and numerical control can be applied to machine tapers, inclines, or complex contours. Wire EDM is a process that can be used on any electrically conducting workpiece, regardless of its mechanical properties, so it can be preferred over processes such as band sawing where wear and dulling of the blade would otherwise be an important concern. With increasing strength and toughness and various other properties of advanced engineering materials, there was a need to develop processes that were not sensitive to these properties. As in all other processes, it has its advantages as well as limitations, regarding particularly the material-removal rate and possible surface damage, which could significantly reduce fatigue life.

9.32 Make a list of the material removal processes described in this chapter that may be suitable for the following workpiece materials: (1) ceramics, (2) cast iron, (3) thermoplastics, (4) thermosets, (5) diamond, and (6) annealed copper. Explain.

By the student. It will be noted that, as described in Chapter 8, most of these materials can be machined through conventional means. Consider the following processes:

(a) Ceramics: water-jet machining, abrasive-jet machining, chemical machining.

(b) Cast iron: chemical machining, electrochemical machining, electrochemical grinding, EDM, laser-beam and electron-beam machining, and water- and abrasive-jet machining.

(c) Thermoplastics: water-jet and abrasive-jet machining; electrically-conducting polymers may be candidates for EDM processing.

(d) Thermosets: similar consideration as for thermoplastics.

(e) Diamond: None, because diamond would not be responsive to any of the methods described in this chapter.

(f) Annealed copper: Chemical and electrochemical processes, EDM, and laser-beam machining.

9.33 Explain why producing sharp corners and profiles using some of the processes described in this chapter can be difficult.

By the student. Some of the processes are functionally constrained and cannot easily provide very small radii. Consider water-jet machining: the minimum radius which can be cut will depend on the ability to precisely focus the water jet. With wire EDM, the minimum radius depends on the wire diameter. Small radii are possible with small wires, but small wires have low current-carrying capacity, thus compromising the speed of the process. With laser-beam cutting, radii are adversely affected by material melting away from the cutting zone, as well as beam diameter. Similar problems exist in chemical machining as the chemical tends to remove a wider area than that required for sharp profiles.

9.34 How do you think specific energy, u, varies with respect to wheel depth of cut and hardness of the workpiece material? Explain.

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The specific energy, u, will decrease with increasing depth of cut, d, according to the size effect, discussed on p. 533. It will increase with workpiece hardness because of the higher strength and hence the more energy required. An increase in the wheel depth of cut will result in higher forces on the grains, as seen in Eq. (9.6) on p. 532. Increasing workpiece hardness also means higher forces.

9.35 It is stated in Example 9.2 that the thrust force in grinding is about 30% higher than the cutting force. Why is it higher?

We note in Fig. 9.7 that abrasive grains typically have very high negative rake angles. Let's now compare the force differences in grinding with that for machining. Referring to Fig. 8.12 we note that as the rake angle decreases, the thrust force increases rapidly. Inspecting the data in Tables 8.1 and 8.2 on pp. 430-431, we note the same phenomenon, and particularly the fact that the difference between the two forces becomes smaller as the rake angle becomes negative. Based on these observations, it is to be expected that the thrust force in grinding will be higher than the cutting force.

9.36 Why should we be interested in the magnitude of the thrust force in grinding? Explain.

By the student. Major considerations include the fact that the thrust force determines the strength required in supporting the grinding wheel on the machine. Note also the load that is exerted onto the workpiece, which influences the elastic recovery in the workpiece and thus affect the dimensional accuracy.

9.37 Why is the material removal rate in electrical-discharge machining a function of the melting point of the workpiece material? Explain.

By the student. As described in Section 9.13, material removal in EDM is accomplished by melting small amounts of material through sparks supplied by electrical energy. Consequently, the higher the melting point, the higher the energy required.

9.38 Inspect Table 9.4 and, for each process, list and describe the role of various mechanical, physical, and chemical properties of the workpiece material on performance.

By the student. This problem is a good topic for classroom discussion. Students may, for example, be asked which of the processes are affected by hardness, melting temperature, and electrical and thermal conductivity.

9.39 Which of the processes listed in Table 9.4 would not be applicable to nonmetallic materials? Explain.

By the student. The following are generally not applicable to nonmetallic materials: electrochemical machining, electrochemical grinding, EDM, and wire EDM.

9.40 Why does the machining cost increase rapidly as surface finish requirements become finer?

By the student. As surface finish requirements become finer, the depth of cut must be decreased, and the grit size must also be decreased. The operation must be carried out carefully using rigid machines, proper control of processing variables, and effective metalworking fluids. These generally lead to longer machining times and thus higher costs.

9.41 Which of the processes described in this chapter are particularly suitable for workpieces made of (a) ceramics, (b) thermoplastics, and (c) thermosets? Explain.

By the student. Note that many processes have limited suitability for difficult-to-process workpieces. However, an example of an acceptable answer is:

(a) Ceramics: grinding, ultrasonic machining, chemical machining;

(b) thermoplastics: chemical machining, high-energy-beam machining, water-jet and abrasive-jet machining;

(c) thermosets: grinding, ultrasonic machining, chemical machining, and water-jet and abrasive-jet machining.

9.42 Other than cost, is there a reason that a grinding wheel intended for a hard workpiece cannot be used for a softer workpiece? Explain.

By the student. Recall that a soft workpiece may load a grinding wheel unless it is specifically intended for use on that material. This

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would mean that the grinding wheel would need to be dressed and trued more often for efficient grinding.

9.43 How would you grind the facets on a diamond, such as for a ring, since diamond is the hardest material known?

Diamond grinding is typically done using fine diamond powder. It should be realized that just because diamond is the hardest material known does not mean that it does not wear. Hardness not only arises from material properties but also local geometry (see Section 2.6), so at the asperity scale it is possible for abrasion to occur on diamond.

9.44 Define dressing and truing, and describe the difference between them.

These two terms are sometimes confused or difficult to differentiate, since they usually are performed at the same time. As discussed in Section 9.5.1, dressing is the process of conditioning worn grains to expose new and aggressive grains. Truing involves reshaping an out-of-round wheel.

9.45 What is heat checking in grinding? What is its significance? Does heat checking occur in other manufacturing processes? Explain.

Heat checking refers to small surface cracks on a workpiece, and in grinding this is caused by high stresses and excessively high temperatures (see also section 9.4.3). Heat checking is often associated with development of tensile residual stresses on a surface. This is significant because it compromises both the fatigue properties of the workpiece as well as its appearance. Heat checking also occurs in casting, especially in die casting.

9.46 Explain why parts with irregular shapes, sharp corners, deep recesses, and sharp projections can be difficult to polish.

By the student. Students are likely to have had some experience relevant to this question. The basic reason why these shapes may be difficult to polish is that it is difficult to have a polishing medium to can properly follow an intricate surface, penetrate corners or depths, and be able to apply equal pressure on all surfaces for uniform polishing.

9.47 Explain the reasons why so many different deburring operations have been developed over the years.

By the student. There are several deburring operations because of the wide variety of workpiece materials, their characteristics, shapes, surface features, and textures involved. There is also the requirement for different levels of automation in deburring operations.

9.48 Note from Eq. (9.9) that the grinding temperature decreases with increasing work speed. Does this mean that for a work speed of zero, the temperature is infinite? Explain.

Consider the heat flow in grinding: The heat source is at the wheel/workpiece interface and is caused by the work of plastic deformation in producing chips and by friction (as it is in metal cutting). The heat is removed through the following mechanisms:

(a) Chips leaving the ground surface.
(b) By conduction to the workpiece
(c) By convection in the workpiece, with the heat being physically moved with the material.
(d) By the grinding fluid, if used.
(e) Radiation, although this is usually much smaller than the other forms of heat transfer in the system.

According to the equation (which is an approximation), decreasing the work speed will increase the temperature, but the temperature cannot be infinite because there are still the other means of heat transfer listed above.

9.49 Describe the similarities and differences in the action of metalworking fluids in machining vs. grinding operations.

Compare the contents of Sections 8.7 and 9.6.9. From a functional standpoint, the purposes of these fluids are primarily cooling and lubricating to reduce friction, temperature, wear, and power requirements. There are many similarities between the two groups, including chemical, rheological, and tribological properties. As

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for differences, note that the dimensions involved in grinding are much smaller than those in machining, and consequently the fluids must be able to penetrate the small interfaces. Thus, properties such as viscosity, wetting, surface-tension characteristics, and method of application would be more important in grinding. (See also Section 4.4.3.)

9.50 Are there any similarities among grinding, honing, polishing, and buffing? Explain.

By the student. All of these processes use abrasive particles of various types, sizes, and shapes, as well as various equipment to remove material in very small amounts. Based on the details of each process described in this chapter, the student should elaborate further on this topic.

9.51 Is the grinding ratio an important factor in evaluating the economics of a grinding operation? Explain.

A high grinding ratio, G, is high, means that much material is removed with relatively little wear of the grinding wheel. Note, however, that this is not always desirable because it could indicate that abrasive grains may be dulling, raising the workpiece temperature and possibly causing surface damage. Low grinding ratios, on the other hand, indicate high wheel-wear rate, leading to the need to dress wheels more frequently and eventually replacing the whole wheel. These considerations also involve the cost of the wheel, as well as the costs incurred in replacing the wheel and the economic impact of having to interrupt the production run. Consequently, as in all aspects of manufacturing, an optimum set of parameters have to be established to minimize any adverse economic impact.

9.52 Although grinding can produce a very fine surface finish on a workpiece, is this necessarily an indication of the quality of a part? Explain.

The answer is not necessarily so because surface integrity includes factors in addition to surface finish (which is basically a geometric feature). As stated on p. 133, surface integrity includes several mechanical and metallurgical parameters which, in turn, can have adverse effects on the performance of a ground part, such as its strength, hardness, and fatigue life. The students are encouraged to explore this topic further.

9.53 If not performed properly, honing can produce holes that are bellmouthed, wavy, barrel-shaped, or tapered. Explain how this is possible.

If the honing tool is mounted properly on its center and the axis of the tool is aligned with the axis of the hole, the hole will be cylindrical. However, if this is not the case, the path followed by the hone will not be circular. Its shape will depend on the geometric relationships of the axes involved. This topic could be interesting exercise in solid and descriptive geometry, referring also to the literature on honing practices.

9.54 Which of the advanced machining processes described in this chapter causes thermal damage to workpieces? List and explain the possible consequences of such damage.

The advanced machining processes which cause thermal damage are obviously those that involve high levels of heat, that is, EDM, laser-beam, and electron-beam machining. The thermal effect can cause the material to develop a heat-affected zone (see Fig. 12.15), thus adversely affecting hardness and ductility. For the various effects of temperature in machining and grinding, see Sections 8.2.6 and 9.4.3, respectively.

9.55 Describe your thoughts regarding laser-beam machining of nonmetallic materials. Give several possible applications and include their advantages as compared to other processes.

By the student. Most nonmetallic materials, including polymers and ceramics, can be laser-beam machined using different types of lasers. The presence of a concentrated heat source and its various adverse effects on a particular material and workpiece must of course be considered. Some materials can involve additional concerns; wood, for example, is flammable and may require an oxygen-free environment.

9.56 It was stated that graphite is the generally preferred material for EDM tooling. Would

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graphite also be appropriate for wire EDM? Explain.

It is presently impossible to produce graphite wires, although significant effort has been directed towards impregnating tungsten wire with graphite to improve its performance in EDM. An important consideration is their lack of ductility, which is essential in wire EDM (note the spools and wire guides in Fig. 9.35). Such hybrid wires have considerable promise, but to date they have not produced sufficient utility, especially when compared to their cost.

9.57 What is the purpose of the abrasives in electrochemical grinding? Explain.

By the student. The purpose of the abrasives in electrochemical grinding are described in Section 9.12. Namely, they act as insulators and, in the finishing stages, help produce a surface with good surface finish and dimensional accuracy.

Problems

9.58 In a surface-grinding operation, calculate the chip dimensions for the following process variables: $D = 8$ in., $d = 0.001$ in., $v = 30$ ft/min, $V = 5000$ ft/min, $C = 500$ per in^2, and $r = 20$.

The approximate chip length, l, is given by Eq. (9.1) on p. 530 as

$$l = \sqrt{Dd} = \sqrt{(8)(0.001)} = 0.0894 \text{ in.}$$

The undeformed chip thickness, t, is given by Eq. (9.5) on p. 532 as

$$\begin{aligned} t &= \sqrt{\frac{4v}{VCr}}\sqrt{\frac{d}{D}} \\ &= \sqrt{\frac{4(30)}{(5000)\,(500)\,(20)}}\sqrt{\frac{0.001}{8}} \\ &= 1.64 \times 10^{-4} \text{ in.} \end{aligned}$$

9.59 If the workpiece strength in grinding is increased by 50%, what should be the percentage decreases in the wheel depth of cut, d, in order to maintain the same grain force, all other variables being the same?

From Section 9.4.1, it is apparent that if the workpiece-material strength is doubled, the grain force will be doubled. Since the grain force is dependent on the square root of the depth of cut, the new depth of cut would be one-fourth the original depth of cut. Thus, the reduction in the wheel depth of cut would be 75%.

9.60 Taking a thin, Type 1 grinding wheel, as an example, and referring to texts on stresses in rotating bodies, plot the tangential stress, σ_t, and radial stress, σ_r, as a function of radial distance (from the hole to the periphery of the wheel). Note that because the wheel is thin, this situation can be regarded as a plane-stress problem. How would you determine the maximum combined stress and its location in the wheel? Explain.

The tangential and radial stresses in a rotating cylinder are given, respectively, by (see Hamrock, Jacobson, and Schmid, *Fundamentals of Machine Elements*, McGraw-Hill, 1999, p. 401)

$$\sigma_\theta = \frac{3+\nu}{9}\rho\omega^2\left[r_i^2 + r_o^2 + \frac{r_i^2 r_o^2}{r^2} - \frac{1+3\nu}{3+\nu}r^2\right]$$

and

$$\sigma_r = \frac{3+\nu}{8}\rho\omega^2\left[r_i^2 + r_o^2 - \frac{r_i^2 r_o^2}{r^2} - r^2\right]$$

where ρ is the material density, ω is the angular velocity, r_i and r_o are the inner and outer radii, respectively, and ν is Poisson's ratio for the material. These are plotted as follows:

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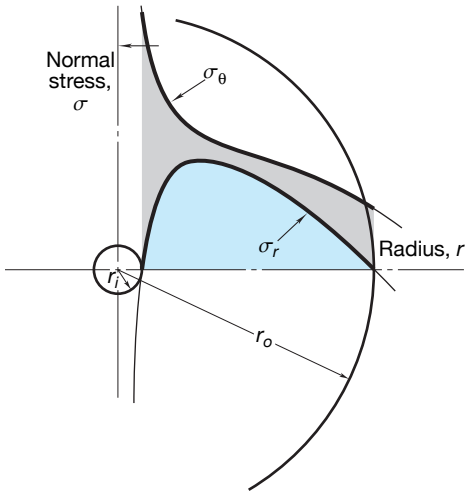

The combined stresses can be calculated for each radial position by referring to Section 2.11.

9.61 Derive a formula for the material removal rate in surface grinding in terms of process parameters. Use the same terminology as in the text.

The material removal rate is defined as

$$\text{MRR} = \frac{\text{Volume of material removed}}{\text{Time}}$$

In surface grinding, the situation is similar to the metal removal rate in slab milling (see Section 8.10.1). Therefore,

$$\text{MRR} = \frac{lwd}{t} = vwd$$

where w is the width of the grinding wheel.

9.62 Assume that a surface-grinding operation is being carried out under the following conditions: $D = 250$ mm, $d = 0.1$ mm, $v = 0.5$ m/s, and $V = 50$ m/s. These conditions are then changed to the following: $D = 150$ mm, $d = 0.1$ mm, $v = 0.3$ m/s, and V=25 m/s. What is the difference in the temperature rise from the initial condition?

The temperature rise is given by Eq. (9.9) on p. 535. Note that the value of C is not known, but we can assume that it does not change between the two cases, so it can be ignored in this analysis. For the initial case, we have

$$\begin{aligned}\Delta T &\propto D^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{0.5} \\ &\propto (250)^{1/4}(0.1)^{3/4}\left(\frac{50}{0.5}\right)^{0.5} = 7.071\end{aligned}$$

For the second case, we have

$$\begin{aligned}\Delta T &\propto D^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{0.5} \\ &\propto (150)^{1/4}(0.1)^{3/4}\left(\frac{25}{0.3}\right)^{0.5} = 5.681\end{aligned}$$

Therefore, we expect the temperature to decrease, with the temperature rise to be about 20% lower in the second case.

9.63 For a surface-grinding operation, derive an expression for the power dissipated in imparting kinetic energy to the chips. Comment on the magnitude of this energy. Use the same terminology as in the text.

The power, P, in terms of kinetic energy per unit time, can be expressed as

$$P = \frac{1}{2}\left(\frac{\text{Volume of chips}}{\text{Time}}\right)\rho V^2$$

or

$$P = \frac{1}{2}w\left(\frac{rt^2}{4}\right)(VC\rho)\left(V^2\right)$$

Since

$$\left(\frac{rt^2}{4}\right)(VC) = vd$$

we have

$$P = \frac{dw\rho V^2 v}{2}$$

The same expression can be derived by noting that the volume of the chips removed is dwL, where L is the length ground. The work done in imparting velocity V to the chips is

$$\text{Work} = \frac{mV^2}{2} = \frac{dwL\rho V^2}{2}$$

Since power is the time rate of work,

$$P = \frac{dW}{dt} = \frac{dw\rho V^2}{2}\frac{dL}{dt} = \frac{dw\rho V^2 v}{2}$$

which is the same expression as before.

9.64 The shaft of a Type 1 grinding wheel is attached to a flywheel only, which is rotating at a certain initial rpm. With this setup, a surface-grinding

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operation is being carried out on a long workpiece and at a constant workpiece speed, v. Obtain an expression for estimating the linear distance ground on the workpiece before the wheel comes to a stop. Ignore wheel wear.

By the student. Note that, because of the variables involved, there will be many possible answers. The specific energy (energy per unit volume) is given by Eq. (9.7) as

$$u = u_{\text{chip}} + u_{\text{plowing}} + u_{\text{sliding}}$$

The magnitude of u_{chip} can be found using a negative rake angle and the material properties as described in Chapter 8. u_{plowing} can be found through various means, including upper-bound analysis. Equating the energy in the flywheel to the work done per unit length plowed, one can then calculate the total length.

9.65 Calculate the average impact force on a steel plate by a 1-mm spherical aluminum-oxide abrasive grain, dropped from heights of (a) 1 m, (b) 2 m, and (c) 10 m. Plot the results and comment on your observations.

(a) The velocity of the particle as it strikes the surface from an initial height of one meter is given by

$$v = \sqrt{2gh} = \sqrt{2(9.81 \text{ m/s}^2)(1 \text{ m})} = 4.43 \text{ m/s}$$

The solid wave velocity in the workpiece is given by

$$c = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{200 \times 10^9 \text{ Pa}}{7680 \text{ kg/m}^3}} = 5103 \text{ m/s}$$

and hence the contact time is calculated from Eq. (9.11) as

$$t_o = \frac{5r}{c_o}\left(\frac{c_o}{v}\right)^{1/5} = \frac{5(0.0005)}{5000}\left(\frac{5000}{4.43}\right)^{1/5}$$

or $t_o = 2.01 \times 10^{-6}$ s. From Table 11.7, the density of aluminum oxide is, on average, 4250 kg/m^3. Therefore, the mass of the particle is

$$m = \frac{4}{3}\pi d^3\rho = \frac{4}{3}\pi(0.001)^3(4250)$$

or $m = 1.78 \times 10^{-5}$ kg. Therefore, from Eq. (9.13),

$$F_{\text{ave}} = \frac{2mv}{t_o} = \frac{2(1.78 \times 10^{-5})(4.43)}{2.04 \times 10^{-6}}$$

or $F_{\text{ave}} = 77.3$ N

(b) Repeating this calculation for a height of 2 m gives a force of $F_{\text{ave}} = 119$ N.

(c) For a height of 10 m, $F_{\text{ave}} = 312.7$ N.

Note that these calculations are for free fall and do not include air resistance on the particle.

9.66 A 50-mm-deep hole, 25 mm in diameter, is being produced by electrochemical machining. Assuming that high production rate is more important than the quality of the machined surface, estimate the maximum current and the time required to perform this operation.

The maximum current density for electrochemical machining is 8 A/mm^2 (see Table 9.4 on p. 554). The area of the hole is

$$A = \frac{\pi D^2}{4} = \frac{\pi(25)^2}{4} = 491 \text{ mm}^2$$

The current is the product of the current density and the cathode area, which is assumed to be the same as the cross-sectional area of the hole. Thus,

$$i = \left(8 \text{ A/mm}^2\right)\left(491 \text{ mm}^2\right) = 3927 \text{ A}$$

Note also that the maximum material removal rate in Table 9.4 (given in terms of penetration rate) is 12 mm/min. Since the depth of the hole is 50 mm, the time required is

$$t = \frac{50 \text{ mm}}{12 \text{ mm/min}} = 4.17 \text{ min}$$

9.67 If the operation in Problem 9.66 were performed on an electrical-discharge machine, what would be the estimated machining time?

For electrical discharge machining, Table 9.4 gives the material removal rate as typically 300 mm^3/min. The volume to be removed is

$$V = Ah = (491)(50) = 24,550 \text{ mm}^3$$

hence the time required is

$$t = \frac{24,550 \text{ mm}^3}{300 \text{ mm}^3/\text{min}} = 81.83 \text{ min}$$

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The required time could, however, be much less. If, for example, a through hole is being machined, then the entire hole volume does not have to be machined, only a volume associated with the hole periphery, the depth of the hole, and the kerf (known as *trepanning*). For large blind holes or for deep cavities, a more common approach is to rough machine by end milling (see Fig. 8.1d), then follow EDM.

9.68 A cutting-off operation is being performed with a laser beam. The workpiece being cut is $\frac{1}{4}$ in. thick and 4 in. long. If the kerf is $\frac{1}{6}$ in. wide, estimate the time required to perform this operation.

From Table 9.4, a typical traverse rate is 0.5-7 m/min. For a 4 in. (0.10 m) length, the range of machining time is 12-0.85 s. The $\frac{1}{4}$-in. workpiece thickness is a moderate workpiece thickness, so an average traverse rate is a reasonable approximation. Therefore, an estimate for machining time is around 6 s. It should be recognized, however, that the time required will depend greatly on the power available in the machinery.

9.69 Referring to Table 3.3, identify two metals or metal alloys that, when used as workpiece and electrode, respectively, in EDM would give the (1) lowest and (2) highest wear ratios, R. Calculate these quantities.

(1) For lowest wear ratio (workpiece to electrode): tungsten/lead alloys ($R = 0.00266$), although the use of lead would be unrealistic for such an application. (2) For highest wear ratio: lead alloys/tungsten ($R = 1902$). An example of a more realistic value of the highest wear ratio is for tungsten electrode/tantalum workpiece ($R = 3.03$).

9.70 It was stated in Section 9.5.2 that, in practice, grinding ratios typically range from 2 to 200. Based on the information given in Section 9.13, estimate the range of wear ratios in electrical-discharge machining and then compare them with grinding ratios.

For grinding ratios we refer to Section 9.5.2, where we note that this ratio ranges between 2 and 200, and even higher. Thus, the values are very comparable.

9.71 It is known that heat checking occurs when grinding under the following conditions: Spindle speed of 4000 rpm, wheel diameter of 10 in., and depth of cut of 0.0015 in., and a feed rate of 50 ft/min. For this reason, the spindle speed is to be kept at 3500 rpm. If a new, 8-in-diameter wheel is now used, what should be the spindle speed before heat checking occurs? What spindle speed should be used to maintain the same grinding temperatures as those encountered with the existing operating conditions?

Heat checking is associated with high surface temperatures, so the temperature rise given by Eq. (9.9) on p. 535 will be used to solve this problem. For the known case where heat checking occurs, the velocity is calculated to be

$$V = r\omega = (5)(4000)\left(\frac{1}{12}\right) = 1667 \text{ ft/min}$$

Eq. (9.9) gives

$$\Delta T \propto D^{1/4} d^{3/4} \left(\frac{V}{v}\right)^{1/2}$$

or

$$\begin{aligned} \Delta T &= AD^{1/4} d^{3/4} \left(\frac{V}{v}\right)^{1/2} \\ &= A(10)^{1/4}(0.0015)^{3/4}\left(\frac{1667}{50}\right)^{1/2} \\ &= 0.0783A \end{aligned}$$

where A is a constant. The known safe operating condition has a speed of 1460 ft/min. This leads to a temperature rise of

$$\begin{aligned} \Delta T &= AD^{1/4} d^{3/4} \left(\frac{V}{v}\right)^{1/2} \\ &= A(10)^{1/4}(0.0015)^{3/4}\left(\frac{1460}{50}\right)^{1/2} \\ &= 0.0732A \end{aligned}$$

If an 8-in. wheel is used, the speed at which heat checking occurs is:

$$\begin{aligned} 0.0783A &= AD^{1/4} d^{3/4} \left(\frac{V}{v}\right) \\ &= A(8)^{1/4}(0.0015)^{3/4}\left(\frac{V}{50}\right)^{0.5} \end{aligned}$$

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or $V = 1865$ ft/min. This indicates a spindle speed of 5600 rpm. For the known safe condition, we perform the same calculation using $\Delta T = 0.0732A$ to obtain:

$$\begin{aligned} 0.0732A &= AD^{1/4}d^{3/4}\left(\frac{V}{v}\right) \\ &= A(8)^{1/4}(0.0015)^{3/4}\left(\frac{V}{50}\right)^{0.5} \end{aligned}$$

or $V = 1630$ ft/min. This corresponds to a spindle speed of 4900 rpm.

9.72 A hard aerospace aluminum alloy is to be ground. A depth of 0.003 in. is to be removed from a cylindrical section 8 in. long and with a 3-in. diameter. If each part is to be ground in not more than one minute, what is the approximate power requirement for the grinder? What if the material is changed to a hard titanium alloy?

The volume to be removed is

$$\text{Volume} = \pi D_{\text{avg}} dl = \pi(3 - 0.003)(0.003)(8)$$

or 0.226 in^3. Therefore, the minimum metal removal rate is 0.226 in^3/min. Taking the specific energy requirement as 10 hp-min/in^3 (see Table 9.3), the power requirement is

$$P = (10 \text{ hp-min/in}^3)(0.226 \text{ in3/min}) = 2.26 \text{ hp}$$

For the hard titanium, let $u = 20$ hp-min/in^3; thus, the new power would be 4.52 hp.

9.73 A grinding operation is taking place with a 10-in. grinding wheel at a spindle rotational speed of 4000 rpm. The workpiece feed rate is 50 ft/min, and the depth of cut is 0.002 in. Contact thermometers record an approximate maximum temperature of 1800°F. If the workpiece is steel, what is the temperature if the spindle speed is increased to 5000 rpm? What if it is increased to 10,000 rpm?

At a rotational speed of 4000 rpm, the surface speed is

$$V = r\omega = (5)(4000)\left(\frac{1}{12}\right) = 1667 \text{ ft/min}$$

The temperature rise for $d = 0.002$ in., $v = 50$ ft/min, and $D = 10$ in. is 1800°F; therefore, Eq. (9.9) gives

$$\Delta T \propto D^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2}$$

or

$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2}$$

so that

$$1800°\text{F} = A(10)^{1/4}(0.002)^{3/4}\left(\frac{1667}{50}\right)^{1/2}$$

hence $A = 18,500$. If the spindle speed is now 5000 rpm, or a surface speed of 2080 ft/min, the temperature rise will be

$$\begin{aligned} \Delta T &= AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} \\ &= (18,500)(10)^{1/4}(0.002)^{3/4}\left(\frac{2080}{50}\right)^{1/2} \\ &= 2010°\text{F} \end{aligned}$$

At a spindle speed of 10,000 rpm, the surface speed is 4167 ft/min, and the temperature rise is

$$\begin{aligned} \Delta T &= AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} \\ &= (18,500)(10)^{1/4}(0.002)^{3/4}\left(\frac{4167}{50}\right)^{1/2} \\ &= 2840°\text{F} \end{aligned}$$

Note that this temperature is above the melting point of steel (see Table 3.3 on p. 106). Clearly, the temperature cannot increase above the melting point of the workpiece material. This indicates that the 10,000 rpm speed, combined with the other process parameters, would not be a realistic process parameter.

9.74 The regulating wheel of a centerless grinder is rotating at a surface speed of 25 ft/min and is inclined at an angle of 5°. Calculate the feed rate of material past the grinding wheel.

The feed rate is merely the component of the velocity in the feed direction, given by

$$f = V \sin\alpha = (25 \text{ ft/min})(\sin 5°)$$

or $f = 2.18$ ft/min or 0.44 in./s.

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9.75 Using some typical values, explain what changes, if any, take place in the magnitude of the impact force of a particle in ultrasonic machining of a hardened-steel workpiece as its temperature is increased?

Inspecting Eqs. (9.11) and (9.13) we can see that the force of a particle on a surface is given by

$$F_{\text{ave}} = \frac{2mv}{\left[\frac{5r}{c_o}\left(\frac{c_o}{v}\right)^{1/5}\right]} = \frac{2mv^{6/5}c_o^{4/5}}{5r}$$
$$= \frac{2mv^{6/5}E^{2/5}}{5r\rho^{2/5}}$$

From Fig. 2.9, the stiffness of carbon steel over a temperature increase of 700°C changes from 27 to 20 $\times$ 10^6 psi. For the same temperature range, there is a thermal strain of

$$\epsilon = 1 + \alpha\Delta T = 1 + \left(11.7 \times 10^{-6}\right)(700)$$

or $\epsilon = 1.00819$. Comparing the two states, one at room temperature and the other at elevated temperature, and noting that the density is affected by thermal strain, we can write

$$\frac{F_{\text{ave},1}}{F_{\text{ave},2}} = \frac{\left(\frac{2mv^{6/5}E_1^{0.4}}{5r\rho_1^{0.4}}\right)}{\left(\frac{2mv^{6/5}E_2^{0.4}}{5r\rho_2^{0.4}}\right)}$$
$$= \left(\frac{E_1}{E_2}\right)^{0.4}\left(\frac{\rho_2}{\rho_1}\right)^{0.4}$$
$$= \left(\frac{E_1}{E_2}\right)^{0.4}\left(\frac{\epsilon_1^3}{\epsilon_2^3}\right)^{0.4}$$

Since $E_1/E_2 = 20/27$ and $\epsilon_1/\epsilon_2 = (0.00819)^3$, we calculate the right-hand side of this equation as 0.89. Therefore, it can be concluded that the force decreases with an increase in temperature. It should be noted, however, that the change is small. For example, a 700°C temperature rise is required for a force reduction of around 10%.

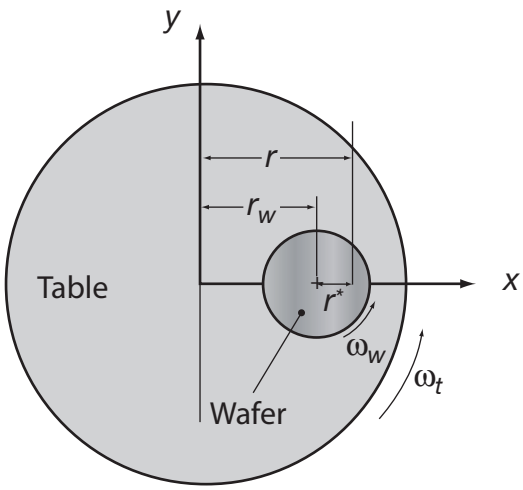
9.76 Estimate the percent increase in the cost of the grinding operation if the specification for the surface finish of a part is changed from 63 to 16 μin.

Referring to Fig. 9.41, note that changing the surface finish from 63 μin. to 16 μin. would involve an increased cost of about 400%. This is a very significant increase in cost, and is a good example of the importance of the statement made throughout the book that, in order to minimize manufacturing costs (see also Fig. 16.6), dimensional accuracy and surface finish should be specified as broadly as is permissible.

9.77 Assume that the energy cost for grinding an aluminum part is \$0.90 per piece. Letting the specific energy requirement for this material be 8 Ws/mm^3, what would be the energy cost if the workpiece material is changed to T15 tool steel?

From Table 9.3 on p. 534, note that the power requirement for T15 tool steel ranges from 17.7 to 82 W-s/mm^3. Consequently, the costs would range from 2.5 to 11.7 times that for the aluminum. This means an energy cost between \$2 and \$9.36 per part.

9.78 Derive an expression for the angular velocity of the wafer as a function of the radius and angular velocity of the pad in chemical mechanical polishing.



By the student. Refer to the figure above and consider the case where a wafer is placed on the x-axis, as shown. Along this axis there is no velocity in the x-direction. The y-component of the velocity has two sources: the rotation of

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the table and the rotation of the carrier. Considering the table movement only, the velocity distribution can be expressed as

$$V_y = r\omega_t$$

and for the carrier

$$V_y = r^*\omega_w$$

where r^* can be positive or negative, and is shown positive in the figure. Note that $r = r_w + r^*$, so that we can substitute this equation into V_y and combine the velocities to obtain the total velocity as

$$V_{y,\text{tot}} = (r_w + r^*)\omega_t + r^*\omega_w$$

If $\omega_w = -\omega_t$, then $V_{y,\text{tot}} = r_w\omega_t$. Since the location of the wafer and the angular velocity of the carrier are fixed, the y-component of velocity is constant across the wafer.

9.79 A 25-mm-thick copper plate is being machined by wire EDM. The wire moves at a speed of 1.5 m/min and the kerf width is 1.5 mm. Calculate the power required. (Assume that it takes 1550 J to melt one gram of copper.)

Note from Table 3.3 on p. 106 that the density of copper is $\rho = 8970$ kg/m^3. The metal removal rate is given by Eq. (9.22) on p. 565 as

$$\text{MRR} = V_f hb = (1500)(25)(1.5)$$

or MRR=56,250 mm^3/min $= 56.25 \times 10^{-6}$ m^3/min. Therefore, we can calculate the rate of mass removal as:

$$\text{Mass MRR} = \rho(\text{MRR}) = (8970)(56.25 \times 10^{-6})$$

or 505 g/min. Therefore, the required power is calculated as

$$P = (505)(1550)\left(\frac{1}{60}\right) = 13,046 \text{ Nm/s}$$

or $P = 13$ kW.

9.80 An 8-in. diameter grinding wheel, 1 in. wide, is used in a surface grinding operation performed on a flat piece of heat-treated 4340 steel. The wheel is rotating with a surface speed $V = 5,000$ fpm, depth of cut $d = 0.002$ in./pass, and cross feed $w = 0.15$ in. The reciprocating speed of the work is $v = 20$ ft/min. and the operation is performed dry. (a) What is the length of contact between the wheel and the work? (b) What is the volume rate of metal removed? (c) Letting $C = 300$, estimate the number of chips produced per unit time. (d) What is the average volume per chip? (e) If the tangential cutting force on the workpiece is $F_c = 10$ lb, what is the specific energy for the operation?

(a) The length of contact between the wheel and the workpiece is given by Eq. (9.1) as

$$l = \sqrt{Dd} = \sqrt{(8)(0.002)} = 0.1265 \text{ in.}$$

(b) The metal removal rate is given by (See Example 9.2 on p. 533):

$$\text{MRR} = dwv = (0.002)(20)(12)(0.15)$$

or MRR $= 0.072$ in^3/min.

(c) The rate of chip production is given by

$$n = VwC = (5000)(12)(0.15)(300)$$

or $n = 2.7 \times 10^6$ chips/min.

(d) The average volume is:

$$\text{Vol} = \frac{\text{MRR}}{\text{Chips/min}} = \frac{0.072}{2.7 \times 10^6}$$

or Vol$= 2.67 \times 10^{-8}$ in^3/chip.

(e) Note that the power required is $P = F_c V$. The specific energy is the ratio of power to material removal rate, or

$$u = \frac{F_c V}{\text{MRR}} = \frac{(10)(5000)(12)}{0.072}$$

or $u = 8.33 \times 10^6$ in-lb/in^3. Since 1 hp=396,000 in-lb/min,

$$u = \frac{8.33 \times 10^6}{396,000} = 21 \text{ hp-min/in}^3$$

As can be seen from Table 9.3, this is a reasonable specific energy for grinding a hard (i.e., heat-treated) steel.

9.81 A 150-mm-diameter tool steel ($u = 60$ W-s/mm^3) work roll for a metal rolling operation is being ground using a 250-mm-diameter, 75-mm-wide, Type 1 grinding wheel. The work roll rotates at 10 rpm. Estimate the chip dimensions and grinding force if $d = 0.04$ mm,

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$N = 3000$ rpm, $r = 12$, $C = 5$ grains per mm^2, and the wheel rotates at $N = 3000$ rpm.

This solution is similar to that given in Example 9.1 on p. 532, except the undeformed chip length, l, is given by Eq. (9.2) since the workpiece is cylindrical. Therefore, the chip length is:

$$l = \sqrt{\frac{Dd}{1 + (D/D_w)}} = \sqrt{\frac{(0.25)(0.00004)}{1 + (0.25)/(0.15)}}$$

which is solved as $l = 0.00194$ m $= 1.94$ mm. Note that the velocities are

$$v = 2\pi rN = 2\pi(0.075)(10) = 4.7 \text{ m/min}$$

or $v = 0.0785$ m/s, and

$$V = r\omega = 2\pi rN = 2\pi(0.075)(3000)$$

or $V = 1413.7$ m/min $= 23.6$ m/s. Therefore, the undeformed chip thickness is given by (see Section 9.4):

$$VC\frac{rt^2 l}{4} = vd \quad or \quad t = \sqrt{\frac{4vd}{VCrl}}$$

Substituting into this expression, t is found to be

$$t = \sqrt{\frac{4(0.0785)(0.00004)}{(23.6)(5)(0.00194)}} = 0.0074 \text{ mm}$$

The material removal rate is

$$\begin{aligned} \text{MRR} &= dwv \\ &= (0.00004)(0.075)(4.7) \\ &= 1.41 \times 10^{-5} \text{ m}^3/\text{min} = 235 \text{ mm}^3/\text{s} \end{aligned}$$

Since u is given as 60 W-s/mm^3, the power consumed will be:

$$P = u(\text{MRR}) = (60)(235) = 14.1 \text{ kW}$$

Also, we know

$$P = F_c V \quad \text{or} \quad F_c = \frac{P}{V}$$

so that

$$F_c = \frac{14,100}{23.6} = 597 \text{ N}$$

9.82 Estimate the contact time and average force for the following particles striking a steel workpiece at 1 m/s. Use Eqs. (9.11) and (9.13) and comment on your findings. (a) 5-mm-diameter steel shot; (b) 0.1-mm-diameter cubic boron nitride particles; (c) 3-mm-diameter tungsten sphere; (d) 75-mm-diameter rubber ball; (e) 3-mm-diameter glass beads. (*Hint:* See Tables 2.1, 3.3 and 8.6.)

The time of contact depends on the elastic wave velocity in the workpiece; for steel, where $E = 195$ GPa (from Table 2.1) and $\rho = 8025$ kg/m^3 (from Table 3.3), the wave velocity is calculated as:

$$c_o = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{195 \times 10^9}{8025}} = 4930 \text{ m/s}$$

Therefore, for the steel shot with a diameter of 5 mm ($r = 0.0025$ m), Eq. (9.11) gives:

$$t_o = \frac{5r}{c_o}\left(\frac{c_o}{v}\right)^{1/5} = \frac{5(0.0025)}{(4930)}\left(\frac{4930}{1}\right)^{1/5}$$

or $t_o = 13.9$ μs. Therefore, the average force exerted is

$$F_{\text{ave}} = \frac{2\pi r^3 \rho v}{t_o} = \frac{2\pi(0.0025)^3(8025)(1)}{13.9 \times 10^{-6}}$$

or $F_{\text{ave}} = 56.7$ N. Using the same calculations, the following table can be constructed:

Material	r (mm)	ρ $\left(\frac{\text{kg}}{\text{m}^3}\right)$	t_o (μs)	F_{ave} (N)
Steel	2.5	8025[1]	13.9	56.7
cBN	0.1	3500[2]	2.77	0.00794
Tungsten	3	19,290[1]	8.32	393.3
Rubber	75	900[1]	208	11,470
Glass	3	2550[1]	8.32	52

Notes:
1. From Table 2.1.
2. From Table 8.6.

Note that these results are reasonable for the cBN particles in part (b), as the values are well within the parameters suggested in Section 9.9. However, as particle size increases, the applicability of the equations is compromised and unreasonable results are obtained. Consider the extreme case of a rubber ball, similar to a toy

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ball that is gently tossed. These equations predict a force of over 1400 N, an answer that is clearly unrealistic. Equations (9.11) and (9.13) are based upon stress waves; for compliant and large objects, the stress waves interact and the contact is *pseudostatic*, so that these equations no longer apply.

9.83 Assume that you are an instructor covering the topics in this chapter, and you are giving a quiz on the quantitative aspects to test the understanding of the students. Prepare three quantitative problems, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

Design

9.84 Would you consider designing a machine tool that combines, in one machine, two or more of the processes described in this chapter? Explain. For what types of parts could such a machine be useful? Make preliminary sketches for such machines.

By the student. This is a valuable though difficult exercise. Note that, in some respects, processes such as chemical mechanical polishing and electrochemical machining satisfy the criteria stated in this problem.

9.85 With appropriate sketches, describe the principles of various fixturing methods and devices that can be used for each of the processes described in this chapter.

By the student. This is an open-ended problem that would also be suitable for a project. The students are encouraged to conduct literature search on the topic, as well as recall the type of fixtures used and described throughout the chapters. See especially Section 14.9.

9.86 As also described in Section 4.3, surface finish can be an important consideration in the design of products. Describe as many parameters as you can that could affect the final surface finish in grinding, including the role of process parameters as well as the setup and the equipment used.

By the student. Note that among major parameters are the grit size and shape of the abrasive, dressing techniques, and the processing parameters such as feed, speed, and depth of cut.

9.87 Size effect in grinding was described in Section 9.4.1. Design a setup and suggest a series of experiments whereby size effect can be investigated.

By the student. Refer to various sources listed in the bibliography. The experiments can be macroscaled by measuring power consumption as a function of chip thickness (see Eq. (9.5) for the important parameters affecting chip thickness). The experiments could also utilize an effective system on a microscale, such as indenters mounted on piezo-electric load cells and dragged across a surface.

9.88 Describe how the design and geometry of the workpiece affects the selection of an appropriate shape and type of a grinding wheel.

By the student. The workpiece shape and size have a direct role on grinding wheel selection (see, for example, pp. 527, 539, and 543). The part geometry places restrictions on the grinding surfaces, such as with gear teeth where the wheel edge radius must be less than the gear tooth notch radius in order to properly grind the teeth. (See also Sections 8.10.7 and 9.6.)

9.89 Prepare a comprehensive table of the capabilities of abrasive machining processes, including the shapes of parts ground, types of machines involved, typical maximum and minimum workpiece dimensions, and production rates.

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By the student. This is a challenging assignment. The following should be considered as an example of the kinds of information that can be contained in such a table.

Process	Abrasives used	Part shapes	Maximum size	Typical surface finish (μm)
Grinding	Al_2O_3 SiC, cBN Diamond	Flat, round or circular	Flat: no limit. Round: 12 in. Circular: 12 in.	0.2
Barrel finishing	Al_2O_3, SiC	Limited aspect ratio	6 in.	0.2
Chemical-mechanical polishing	Al_2O_3, SiC	Flat surfaces	13 in.	0.05 and lower
Shot blasting	Sand, SiO_2	All types	No limit	1-10

9.90 How would you produce a thin circular disk with a thickness that decreases linearly from the center outward?

By the student. If the part is sufficiently thick, one method is to machine it on a CNC milling machine, but the stiffness of the workpiece is an important factor due to cutting forces that would deflect thin parts. A similar method would be grinding the part, using numerical control equipment. A simpler method is to take a round disc with a constant thickness, insert it fully into a chemical-machining solution (Section 9.10), and withdraw it slowly while it is being rotated; such a part has been made successfully by this method. Note that there will be a major difference in production rates.

9.91 Marking surfaces of manufactured parts with letters and numbers can be done not only with labels and stickers but also by various mechanical and nonmechanical means (see also Section 9.14.1). Make a list of some of these methods, explaining their advantages and limitations.

By the student. Processes include laser machining, where the laser path is computer controlled, chemical etching, where a droplet of solution is placed in similar fashion to ink-jet printers, and machining on a CNC milling machine.

9.92 On the basis of the information given in Chapters 8 and 9, comment on the feasibility of producing a 10-mm diameter, 100-mm deep through hole in a copper alloy by (a) conventional drilling and (b) other methods.

By the student. Note that this is a general question and it can be interpreted as either a through hole or a blind hole (in which case it does not specify the shape of the bottom of the hole). Furthermore, the quality of the hole, its dimensional accuracy, and the surface finish of the cylindrical surface are not specified. It is intended that the students be observant and resourceful to ask such questions so as to supply appropriate answers.

Briefly, a through hole with the dimensions specified can easily be drilled; if the dimensional accuracy and surface finish are not acceptable, the hole can subsequently be reamed and honed. Holes can be internally ground, depending on workpiece shape and accuracies required; note, however, that there has to be a hole first in order to be ground internally.

For blind holes, the answers will depend on the required shape of the hole bottom. Drills typically will not produce flat bottom, and will require an operation such as end milling. Internal grinding is possible on an existing hole, noting also the importance of internal corner features (relief) as stated in the design considerations for grinding in Section 9.16.

9.93 Conduct a literature search and explain how observing the color, brightness, and shape of sparks produced in grinding can be a useful guide to identifying the type of material being ground and its condition.

By the student. Various charts, showing pho-

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tographs or sketches of the type and color of sparks produced, have been available for years as a useful but general guide for material identification at the shop level, especially for steels. Some of these charts can be found in textbooks, such as in Fig. 24.15 on p. 458 of *Machining Fundamentals*, by J.R. Walker.

9.94 Visit a large hardware store and inspect the various grinding wheels on display. Make a note of the markings on the wheels and, based on the marking system shown in Figs. 9.4 and 9.5, comment on your observations, including the most commonly found types and sizes of wheels in the store.

By the student. This is a good opportunity to encourage students to gain some exposure to grinding wheels. The authors have observed an increased reluctance on students to gain practical experience and exposure to machinery by actually visiting vendors, and have found this exercise to be very valuable. The markings on grinding wheels will have the type of information given in Figs. 9.4 or 9.5. It will also be noted that the most common grinding wheels are basically the same as those shown in Fig. 9.2. Those in Fig. 9.3 are less common and also more expensive. Students may also comment on sizes; many grinding wheel shapes are available for hobbyists but not on a larger scale.

9.95 Obtain a small grinding wheel and observe its surfaces using a magnifier or a microscope, and compare with Fig. 9.6. Rub the periphery of the wheel while pressing it hard against a variety of flat metallic and nonmetallic materials. Describe your observations regarding (a) the type of chips produced, (b) the surfaces developed, and (c) the changes, if any, to the grinding wheel surface.

By the student. This is a good project and can become a component of a laboratory course.

9.96 In reviewing the abrasive machining processes in this chapter it will noted that some processes use bonded abrasives while others involve loose abrasives. Make two separate lists for these two types and comment on your observations.

By the student. This is an open-ended problem and the following table should be regarded as only an illustration of an answer. The students should give further details, based on a study of each of the processes covered in the chapter.

Process	Comments
Bonded abrasives	
Grinding	These processes are basically similar to each other and have a wide range abrasive sizes, the material removal rates, surface finish, and lay (see Fig. 33.2 on p. 1039).
Belt grinding	
Sanding	
Honing	
Superfinishing	
Loose abrasives	
Ultrasonic machining	A random surface lay is most common for these processes
Chemical-mechanical polishing	
Barrel finishing	
Abrasive-flow machining	

9.97 Based on the topics covered in Chapters 6 through 9, make a comprehensive table of holemaking processes. (a) Describe the advantages and limitations of each method, (b) comment on the quality and surface integrity of the holes produced, and (c) give examples of specific applications.

By the student. This is a challenging topic for students. The statement of the problem implies that holes are to generated on a sheet or a block of solid material, and that it does not include finishing processes for existing holes. It should be recalled that holemaking processes include (a) piercing, (b) punching, (c) drilling and boring, (d) chemical machining, (e) electrochemical machining, (f) electrical-discharge machining, (g) laser-beam and electron-beam machining, and (h) water-jet and abrasive water-jet machining. The students should prepare a comprehensive answer, based on the study of these processes in various chapters.

9.98 Precision engineering is a term used to describe manufacturing high-quality parts with close dimensional tolerances and good surface finish. Based on their process capabilities, make a list of advanced machining processes (in decreasing order of quality of parts produced). Include a brief commentary on each method.

By the student. This is a challenging task. Students should carefully review the contents of Figs. 4.20, 8.26, 9.27, 16.4, and 16.5, as well

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as the relevant sections in the text. Note that the order in such a listing will depend on the size of the parts to be produced, the quantity required, the workpiece materials, and the desired dimensional tolerances and surface finish.

9.99 It can be seen that several of the processes described in this chapter can be employed, either singly or in combination, to produce or finish tools and dies for metalworking operations. Prepare a brief technical paper on these methods, describing their advantages and limitations, and giving typical applications.

By the student. See also Section 6.7. This is a valuable exercise for students, and the responses should include the latest technical innovations, including rapid prototyping and rapid tooling (described in Chapter 10). Traditionally, processes such as casting, die-sinking (such as with an end mill), and plunge EDM was most commonly used for these applications, although polishing and electrochemical grinding may also be used for near-net-shape parts to improve their surface finish. Laser-beam and electrical-discharge machining is sometimes performed to roughen tool and die surfaces for improved material formability (by virtue of its effects on tribological behavior at workpiece-die interfaces).

9.100 List the processes described in this chapter that would be difficult to apply to a variety of nonmetallic or rubberlike materials. Explain your thoughts, commenting on such topics as part geometries and the influence of various physical and mechanical properties of workpiece materials.

By the student. Some materials will be difficult for some of the processes. For example, a chemically inert material will obviously be difficult to machine chemically. Grinding may be difficult if the workpiece is nonmetallic, and the compliance of rubber materials may limit the grinding force (and thus material removal rate) that can be achieved. Furthermore, a rubberlike material may quickly load a grinding wheel, requiring frequent redressing. Recall also that an electrically-insulating material is impossible for EDM; a tough material can be difficult to cut with a water jet; and a shiny or transparent material is difficult for laser machining. Note that it is rare that a workpiece material has all of these properties simultaneously.

9.101 Make a list of the processes described in this chapter in which the following properties are relevant or significant: (a) mechanical, (b) chemical, (c) thermal, and (d) electrical. Are there processes in which two or more of these properties are important? Explain.

By the student. Because the term relevant may be interpreted as subjective, the students should be encouraged to be responsive as broadly as possible. Also, the question can be interpreted as properties that are important in the workpiece or the phenomenon that is the basic principle of the advanced machining process. Some suggestions are:

Mechanical:	Electrochemical grinding, water-jet machining, abrasive-jet machining.
Chemical:	Chemical machining, electrochemical machining, electrochemical grinding.
Thermal:	Chemical machining, electrochemical machining, electrochemical grinding, plunge EDM, wire EDM, laser-beam machining, electron-beam machining.
Electrical:	Electrochemical machining, electrochemical grinding, plunge EDM, wire EDM, electron-beam machining.

Clearly, there are processes (such as chemical machining) where two properties are important: the chemical reactivity of workpiece and reagents, and the corrosion processes (the principle of chemical machining) which are temperature dependent.

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Chapter 10

Properties and Processing of Polymers and Reinforced Plastics; Rapid Prototyping and Rapid Tooling

Questions

10.1 Summarize the most important mechanical and physical properties of plastics in engineering applications.

The most important mechanical and physical properties of plastics are described in Sections 10.3 through 10.8. Students may create summaries of mechanical properties, make comparisons with other material classes, or investigate novel graphical methods of summarizing the properties.

10.2 What are the major differences between the properties of plastics and of metals?

There are several major differences that can be enumerated, as described throughout the chapter. Some examples are:

(a) Plastics are much less stiff than metals.

(b) They have lower strength than metals and are lighter.

(c) The thermal and electrical conductivities of metals are much higher than those for plastics.

(d) There are much wider color choices for plastics than for metals.

10.3 What properties are influenced by the degree of polymerization?

By the student. As described in Section 10.2.1, the degree of polymerization directly influences viscosity. In addition, as can be understood by reviewing Figs. 10.3 and 10.5, a higher degree of polymerization will lead to higher strength and strain hardening in thermoplastics, and will accentuate the rubber-like behavior of networked structures.

10.4 Give applications for which flammability of plastics would be a major concern.

By the student. There are several applications where flammability of plastics is a major concern. These include aircraft, home insulation (thermal and electrical), cookware, clothing, and components for ovens and stoves (including components such as handles and dials). Students should be encouraged to describe additional applications.

10.5 What properties do elastomers have that thermoplastics, in general, do not have?

By the student. By virtue of their chemical structures, elastomers have the capability of returning to their original shape after being

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stretched, while thermoplastics cannot. Elastomers can do so because they have a low elastic modulus and can undergo large elastic deformation without rupture.

10.6 Is it possible for a material to have a hysteresis behavior that is the opposite of that shown in Fig. 10.14, whereby the arrows are counterclockwise? Explain.

If the arrows were counterclockwise, the material would have a hysteresis gain. This would mean that the energy put into the material is lower than the energy recovered during unloading, which, of course, is impossible.

10.7 Observe the behavior of the tension-test specimen shown in Fig. 10.13, and state whether the material has a high or low m value. (See Section 2.2.7.) Explain why.

Recall that the m value indicates the strain rate sensitivity of a material. The material in Fig. 10.13 on p. 598 elongates extensively by orientation of the polymer molecules, thus it would be expected to have high strain-rate sensitivity. This is related to diffuse necking, as opposed to localized necking observed with metals in tension tests (see Fig. 7.1d).

10.8 Why would we want to synthesize a polymer with a high degree of crystallinity?

This is an open-ended question that can be answered in several ways. Students may rely upon particular applications or changes in material properties. One can refer to Section 10.2.1 and Fig. 10.4, and note that a high degree of crystallinity leads to increased stiffness, especially at higher temperatures.

10.9 Add more to the applications column in Table 10.3.

By the student. Some additional examples are:

(a) Mechanical strength: rope, hangers.

(b) Functional and decorative: electrical outlets, light switches.

(c) Housings, etc.: pens, electrical plugs.

(d) Functional and transparent: food and beverage containers, packaging, cassette holders.

(e) Wear resistance: rope, seats.

10.10 Discuss the significance of the glass-transition temperature, T_g, in engineering applications.

By the student. The glass-transition temperature is the temperature where a thermoplastic behaves in a manner that is hard, brittle and glassy below this temperature, and rubbery or leathery above it (see Section 10.2.1). Since thermoplastics begin to lose their load-carrying capacity above this temperature, there is an upper useful temperature range for the plastic. In engineering applications where thermoplastics would be expected to carry a load, the material for the part would have to have a glass transition temperature higher than the maximum temperature to which it would be subjected in service.

10.11 Why does cross-linking improve the strength of polymers?

Cross-linked polymers have additional bonds linking adjacent chains together (see Fig. 10.3 on p. 589). The strength is increased with thermoplastics because these cross links give additional resistance to material flow since they must be broken before the molecules can slide past one another. With thermosets, they represent additional bonds that must be broken before fracture can occur.

10.12 Describe the methods by which optical properties of polymers can be altered.

Optical properties can be altered by additives which can alter the color or translucence of the plastic. Additives can either be dyes or pigments. Recall also that stress whitening makes the plastic appear lighter in color or more opaque. As stated in Section 10.2.1, optical properties are also affected by the degree of crystallinity of the polymer.

10.13 Explain the reasons that elastomers were developed. Based on the contents of this chapter, are there any substitutes for elastomers? Explain.

By the student. Elastomers (Section 10.8) were developed to provide a material that could undergo a large amount of deformation without failure. They provide high friction and nonskid

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surfaces, abrasive-wear resistance, shock and vibration isolation, and protection against corrosion. They are also used in rubber-pad forming operations.

10.14 Give several examples of plastic products or components for which creep and stress relaxation are important considerations.

By the student. Recall that creep in polymers is particularly important in high-temperature, low-stress applications. In low temperature, high-stress circumstances stress relaxation is important. As an example of the importance of creep, consider polymers as pot handles in cookware. As an example of stress relaxation, seat cushions will deform to provide a uniform stress distribution and thus provide better comfort for the occupant.

10.15 Describe your opinions regarding recycling of plastics versus developing plastics that are biodegradable.

By the student. Some arguments may be made are that recycling actually has a cost associated with it, such as costs involved in collecting the materials to be recycled and the energy required in recycling methods. Note also that the properties of the recycled polymer will likely be inferior as compared to the virgin polymer. Biodegradable plastics have drawbacks as well; it is difficult to design them to degrade in the intended time frame, and they may have more failures in service. They can be significantly more expensive than polymers that are not biodegradable.

10.16 Explain how you would go about determining the hardness of the plastics described in this chapter.

Many of the hardness tests described in Section 2.6 (see also Fig. 2.22 on p. 52) are not suitable for polymers, for reasons such as inelastic recovery of the surface indentation and time-dependent stress relaxation. Recall that durometer testing is an appropriate approach for such materials.

10.17 Distinguish between composites and alloys. Give several examples.

By the student. Consider the following:

- Alloys are mixtures of metals, whereas composites are not necessarily metals. Metal-matrix composites require a reinforcement in the form of fibers or whiskers.
- With composites, the reinforcement is much stronger than the matrix. Even in two-phased alloys, where a matrix could be defined, such a difference in strength or stiffness is not necessarily significant.

10.18 Describe the functions of the matrix and the reinforcing fibers in reinforced plastics. What fundamental differences are there in the characteristics of the two materials?

By the student. As described in Section 10.9, consider, for example, the fact that reinforcing fibers are generally stronger and/or stiffer than the polymer matrix. The function of the reinforcement is therefore to increase the mechanical properties of the composite. On the other hand, the fibers are less ductile and generally have limited resistance to chemicals or moisture (graphite, for example, decomposes when exposed to oxygen). The matrix is very resistant to chemical attack and thus protects the fibers.

10.19 What products have you personally seen that are made of reinforced plastics? How can you tell that they are reinforced?

By the student. This is an open-ended question and students can develop a wide variety of answers. Some suggestions are tennis rackets, baseball bats, chairs, and boat hulls. Sometimes, it is readily apparent that the part has been produced through lay-up; other times the fiber reinforcements can be seen directly on the surface of the part.

10.20 Referring to earlier chapters, identify metals and alloys that have strengths comparable to those of reinforced plastics.

By the student. See Table 16.1 on p. 956. A typical comparison is given below:

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Metal (MPa)	Reinforced plastics (MPa)
Magnesium (165-195)	Nylon (70-210)
	Polyester (110-160)
Al alloys (90-600)	ABS (100)
	Acetal (135)
	Nylon (70-210)
	Polycarbonate (110)
	Polyester (110-160)
	Polypropylene (40-100)
Cu alloys (140-1310)	Nylon (70-210)
	Polyester (40-100)
Iron (185-285)	Nylon (70-210)

10.21 Compare the relative advantages and limitations of metal-matrix composites, reinforced plastics, and ceramic-matrix composites.

By the student. This is a challenging question and the students are encouraged to develop a comprehensive table based on their understanding of the contents of this chapter.

10.22 This chapter has described the many advantages of composite materials. What limitations or disadvantages do these materials have? What suggestions would you make to overcome these limitations?

By the student. Consider, for example, two disadvantages as anisotropic properties and possible environmental attack of the fibers (especially water adsorption). Anisotropy, though not always undesirable, can be reduced by having a random orientation of reinforcing materials. Environmental attack of the fibers would cause loss of fiber strength and possibly debonding from the matrix.

10.23 A hybrid composite is defined as a material containing two or more different types of reinforcing fibers. What advantages would such a composite have over other composites?

By the student. The hybrid composite can have tailored properties. Thus, a certain strength level could be obtained at a lower cost by using a combination of fibers, rather than just one fiber. The anisotropic properties could also be controlled in different ways, such as having, for example, Kevlar fibers oriented along the major stress direction and other fibers dispersed randomly in the composite. The student is encouraged to elaborate further in greater detail.

10.24 Why are fibers capable of supporting a major portion of the load in composite materials? Explain.

By the student. Refer to Example 10.4 on p. 617. The reason that the fibers can carry such a large portion of the load is that they are stiffer than the matrix. Although both the matrix and the fibers undergo the same strain, the fibers will this support a larger portion of the load.

10.25 Assume that you are manufacturing a product in which all the gears are made of metal. A salesperson visits you and asks you to consider replacing some of the metal gears with plastic ones. Make a list of the questions that you would raise before making such a decision. Explain.

By the student. Consider, for example, the following questions:

(a) Will the plastic gear retain its required strength, stiffness, and tolerances if the temperature changes during its use?
(b) How acceptable is the wear resistance and fatigue life of the plastic gears?
(c) Is it compatible with meshing metal gears and other components in the gear train?
(d) Are there any backlash problems?
(e) What are its frictional characteristics?
(f) Is the lighter weight of the plastic gear significant?
(g) Is noise a problem?
(h) Is the plastic gear affected adversely by lubricants present?
(i) Will the supplier be able to meet the quantity demanded?
(j) How much cost savings are involved? (See also Section 16.9.)

10.26 Review the three curves in Fig. 10.8, and describe some applications for each type of behavior. Explain your choices.

By the student. See also Section 10.5. Several examples can be given; consider the following simple examples:

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- Rigid and brittle: Handles, because they should not flex significantly.
- Tough and ductile: Helmets, to dissipate the energy from impact without fracturing.
- Soft and flexible: Beverage bottles, because they can flex when dropped and regain their shape and not break, unlike glass bottles.

10.27 Repeat Question 10.26 for the curves in Fig. 10.10.

By the student. See also Section 10.5 and consider the following:

- Low-density polyethylene: nonbreakable food containers with impact strength at low temperatures, such as in freezers.
- High-impact polypropylene: products that that when dropped or in a collision, will not crack at a wide range of temperatures.
- Polyvinyl chloride (PVC): it can be either flexible or hard, and either type can be used for tubing; since it is not too strong or impact resistant, it must be limited to low pressure tubing.
- Polymethylmethacrylate: has moderate strength, good optical properties, and is weather resistant; these properties make them useful for lighting fixtures that do not require high impact resistance.

10.28 Do you think that honeycomb structures could be used in passenger cars? If so, which components? Explain.

By the student. As an example, two suggestions concerning automobiles: (1) Radiators with copper honeycomb structure to improve heat conduction, and (2) passenger compartment walls consisting of honeycomb structures with cavities filled with noise- and vibration-damping materials, making the compartment more sound proof.

10.29 Other than those described in this chapter, what materials can you think of that can be regarded as composite materials?

By the student. Some examples are:

- Wood: a composite consisting of block cells and long fibrous cells.
- Particle board: a composite that is a combination of wood scraps and a binder.
- Winter coat: a layered type of composite consisting of an outer cloth material which is weather resistant and an insulating inner material to prevent loss of body heat.
- Pencil: graphite rod core surrounded by wood covering.
- Walls: consists of a plaster matrix with wood stud or metal reinforcements.

The students are encouraged to cite several other examples.

10.30 What applications for composite materials can you think of in which high thermal conductivity would be desirable? Explain.

By the student. See also Sections 3.9.4 and.3.9.5. Composite materials with high thermal conductivity could be useful as heat exchangers, food and beverage containers, and medical equipment.

10.31 Conduct a survey of a variety of sports equipment, and identify the components that are made of composite materials. Explain the reasons for and advantages of using composites for these specific applications.

By the student. Examples include rackets for tennis, badminton, and racquetball; baseball and softball bats; golf clubs; fishing rods; and skis and ski poles. The main reason is the light weight of these materials, combined with high stiffness and strength, thus resulting in superior performance.

10.32 We have described several material combinations and structures in this chapter. In relative terms, identify those that would be suitable for applications involving one of the following: (a) very low temperatures; (b) very high temperatures; (c) vibrations; and (d) high humidity.

By the student. This is a challenging topic and the students are encouraged to develop responses with appropriate rationale. For example, very low temperature applications require (1) considerations of the polymer or matrix mechanical properties with appropriate ductility

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toughness, (2) warpage that can occur when lowered from room temperature, and (3) thermal stresses that may develop due to differences in thermal expansion between the polymer part and other parts that are in contact. Temperature variations are particularly important, as described in Sections 3.9.4 and 3.9.5.

10.33 Explain how you would go about determining the hardness of the reinforced plastics and composite materials described in this chapter. What type of tests would you use? Are hardness measurements for these types of materials meaningful? Does the size of the indentation make a difference in your answer? Explain.

By the student. The important consideration here is the fact that the smaller the indentation, the more localized the hardness measurement will be (see Section 2.6). Consequently, one can then distinguish the hardness of the matrix and the reinforcements separately by using small indentations. A large indentation, such as resulting from a Brinell test, will only give an overall hardness value. (Note that this is a consideration similar to microhardness testing of individual components of an alloy or of the individual grains.)

10.34 Describe the advantages of applying traditional metalworking techniques to the forming and shaping of plastics.

By the student. Review Section 10.10 and Chapters 6 and 7. Note also that this topic is briefly described in Section 10.10.9. Applying traditional metalworking techniques to shaping of plastics is advantageous for several reasons. Since the stock shapes are similar (sheet, rod, tubing, etc.), well-known and reliable processes can be applied efficiently. Being able to utilize similar machines and many years of research, development, and experience associated with machine design and process optimization will have major significance in plastics applications as well.

10.35 Describe the advantages of cold forming of plastics over other methods of processing.

By the student. See Section 10.10.9 where four main advantages are outlined.

10.36 Explain the reasons that some forming and shaping processes are more suitable for certain plastics than for others.

By the student. Consider, for example, the following: It is difficult to extrude thermosets because curing is not feasible during the continuous extrusion process. Injection molding of composites is difficult because the fluidity of the material is essential to ensure proper filling of the die, but characteristics and presence of the fibers interferes with this process. Plastics which are produced through reaction molding are difficult to produce through other means, and other processes are not readily adaptable to allow sufficient mixing of the two ingredients. These difficulties should, however, be regarded as challenges and thus novel approaches are encouraged. The students are encouraged to develop additional answers.

10.37 Would you use thermosetting plastics in injection molding? Explain.

Thermosetting plastics are suitable for injection molding (Section 10.10.2), although the process is often referred to as *reaction injection molding*; see p. 629. The basic modification which must be made to the process is that the molds must be heated to allow polymerization and cross-linking of the material. The major drawback associated with this change is that, because of the longer cycle times, the process will not have as high a production rate as for thermoplastics.

10.38 By inspecting plastic containers, such as for baby powder, you can see that the lettering on them is raised and not sunk in. Offer an explanation as to why they are molded in that way.

The reason is that in making molds and dies for plastics processing, it is much easier to produce letters and numbers by removing material from mold surfaces, such as by grinding or end milling, similar to carving of wood. As a result, the molded plastic part will have raised letters and numbers. On the other hand, if we want depressed letters on the product itself, the markings on the molds would have to protrude. This is possible to do but would be costly and

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time consuming to make such a mold, and its wear resistance will likely be lower.

10.39 Give examples of several parts that are suitable for insert molding. How would you manufacture these parts if insert molding were not available?

By the student. See also the parts shown in Fig. 10.30 on p. 628. Some common parts are screw drivers with polymer handles, electrical junction boxes with fasteners that are insert molded, screws and studs in polymer parts to aid assembly, and some writing instruments. Usually, these parts would have to be mechanically assembled or adhesively bonded if insert molding was not an option.

10.40 What manufacturing considerations are involved in making a metal beverage container versus a plastic one?

By the student. See also Fig. 16.31 on p. 452 of Kalpakjian and Schmid, *Manufacturing Engineering and Technology,* 3d ed. and the Bibliography at the end of Chapter 16. Since beverage cans are mass produced in the range of millions per day, the processing must be simple and economical. Other important considerations are chilling characteristics, labeling, feel, aesthetics, and ease of opening. Students should comment on all these aspects. Note also that the beverage can must have sufficient strength to prevent from rupturing under internal pressure (which is on the order of about 120 psi), or being dropped, or buckling under a compressive load during stacking in stores. The can should maintain its properties from low temperatures in the refrigerator to hot summer temperatures, especially under the sun in hot climates. Particularly important is the gas permeability of plastic containers which will significantly reduce their shelf life. Also note how soft drinks begin to lose their carbonation in unopened plastic bottles after a certain period of time. (See also Section 10.10.)

10.41 Inspect several electrical components, such as light switches, outlets, and circuit breakers, and describe the process or processes used in making them.

By the student. The plastic components are usually injection molded and then mechanically assembled. Several ingenious designs use insert molding. Integrated circuits and many other electrical components may be potted.

10.42 Inspect several similar products that are made of metals and plastics, such as a metal bucket and a plastic bucket of similar shape and size. Comment on their respective thicknesses, and explain the reasons for their differences, if any.

By the student. Recall that the basic difference between metals and plastics have been discussed in detail in the text. Consider the following examples:

(a) Metal buckets are thinner than plastic ones, and are more rigid; plastic buckets thus have to be thicker because of their much lower elastic modulus, as well as involve designs with higher section modulus.

(b) Mechanical pencils vs. plastic pens; the polymer pens are much thicker, because they must be rigid for its intended use.

(c) Plastic vs. metal forks and spoons; although no major difference in overall size, the plastic ones are more flexible but can be made more rigid by increasing the section modulus (as can be observed by inspecting their designs).

10.43 Make a list of processing methods used for reinforced plastics. Identify which of the following fiber orientation and arrangement capabilities each has: (1) uniaxial, (2) cross-ply, (3) in-plane random, and (4) three-dimensional random.

By the student. An example of a partial answer is the following:

Process	Uniaxial	Cross-ply	In-plane random	3D random
Sheet-molding compound		X		
Tape lay-up	X	X		
Contact molding			X	
Injection molding	X			X
Pultrusion	X			
Pulforming	X			

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10.44 As you may have observed, some plastic products have lids with integral hinges; that is, no other material or part is used at the junction of the two parts. Identify such products, and describe a method for making them.

Such parts with integral lids are produced with one shot in processes such as injection molding. The hinge is actually a much thinner (reduced) section, which can bend easily, thus acting like a hinge. It should be noted that there are significant material requirements that must be met before such a design can be achieved, including stiffness and fatigue strength. Many polymers are ideally suited for such applications.

10.45 Explain why operations such as blow molding and film-bag making are done vertically and why buildings that house equipment for these operations have ceilings 10 m to 15 m (35 ft to 50 ft) high.

They are done vertically so that the gravitational force does not interfere with the operation. The height of ceilings is dictated by product requirements. The height is large enough so that the blown tube can be cooled from a semi-molten state to a solid state suitable for compression, cutting and recoiling.

10.46 Consider the case of a coffee mug being produced by rapid prototyping. Describe how the top of the handle can be manufactured, since there is no material directly beneath the arch of the handle.

By the student. Depending on the process used and the particular shape of the mug handle, this may or may not be a difficult problem; even if difficult, it can be overcome fairly easily. Some processes, such as stereolithography and fused deposition modeling, can allow building of gradual arches, but a coffee mug is probably too severe, and a ceiling design as shown in Fig. 10.49b on p. 649 would have to be used. Other processes such as selective laser sintering and laminated object manufacturing have no need for supports, and thus a coffee mug can be produced easily.

10.47 Make a list of the advantages and disadvantages of each of the rapid-prototyping operations.

By the student. As examples, the students could investigate (a) cost (where FDM, 3DP, STL have advantages over SLS of metals, for example), (b) material properties (see Table 10.8 on p. 646) where selective laser sintering with bronze-infiltrated steel powder would be superior, or (c) dimensional tolerances or surface finish.

10.48 Explain why finishing operations generally are needed for rapid-prototyping operations. If you are making a prototype of a toy car, list the finishing operations you would want to perform.

By the student. The finishing operations required vary for different rapid prototyping applications. For example, in stereolithography, the part has to be cured in order to fully develop its mechanical properties (the laser does not fully cure the photopolymer), and then the part may need to be sanded or finely ground to obtain a desired surface. Also, often decoration is needed for aesthetic purposes. On the other hand, in fused deposition modeling, the finishing operations would involve removal of support material, followed by sanding and painting, whenever necessary. For a prototype of a toy automobile, the finishing processes would be as discussed.

10.49 A current topic of research involves producing parts from rapid-prototyping operations and then using them in experimental stress analysis, in order to infer the strength of the final parts produced by conventional manufacturing operations. List the concerns that you may have with this approach, and outline means of addressing these concerns.

In theory, this technique can be successful for determining the stresses acting on a part of a certain geometry, as long as the part remains in the linear elastic range and the strains are small. However, it is difficult, although not impossible, to infer performance of conventionally manufactured parts, especially, for example, with respect to fatigue or wear. The reason is that the material microstructure and response to loading will be very different than that for a rapid prototyped model.

10.50 Because of relief of residual stresses during curing, long unsupported overhangs in parts from

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stereolithography will tend to curl. Suggest methods of controlling or eliminating this problem.

These problems can be minimized in design by reducing overhangs or changing the support of the overhang. Otherwise, as shown in Fig. 10.49 on p. 649, gussets or ceilings could be used to support the material and minimize curl during curing.

10.51 One of the major advantages of stereolithography and cyberjet is that semi- and fully-transparent polymers can be used, so that internal details of parts can readily be discerned. List parts or products for which this feature is valuable.

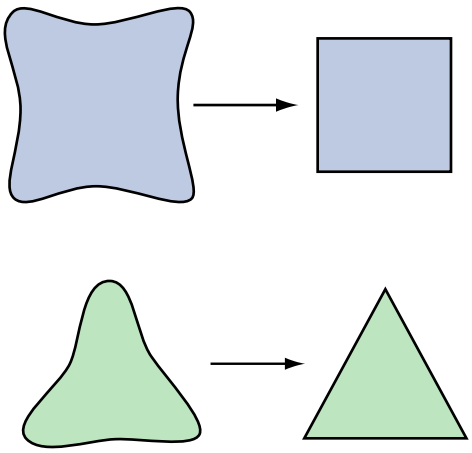
By the student. Some examples are (a) heat exchangers, where the fluid flow can be observed; (b) drug delivery systems, so that any blockage or residual medicines can be observed; (c) any ship-in-the-bottle type of part; d (d) marketing models to explain the internal features of a product.

10.52 Based on the processes used to make fibers as described in this chapter, explain how you would produce carbon foam. How would you make a metal foam?

By the student. This is a good topic for a literature search. One approach is to produce a polymer foam followed by a carburization process, as would be performed to produce graphite powder. The result is a foam produced from carbon, a product that has value as a filter material because of the very large surface area-to-volume ratio. A metal foam can be easily produced at this point by placing the carbon foam in a CVD reactor, whereby the metal will coat the carbon foam. Other alternatives are to blow hot air through molten metal; the froth solidifies into a metal foam, or to use a blowing agent in a P/M process (see Chapter 11).

10.53 Die swell in extrusion is radially uniform for circular cross-sections, but is not uniform for other cross-sections. Recognizing this fact, make a qualitative sketch of a die profile that will produce (a) square and (b) triangular cross-sections of extruded polymer, respectively.

The sketches are given below. Note that there is expected to be greater recovery at corners where the strain on the extruded polymer is highest.



10.54 What are the advantages of using whiskers as a reinforcing material? Are there any limitations?

By the student. Whiskers are much stronger than other fibers because of their small size and lack of defects (see pp. 105 and 463). Whiskers will yield composite materials with higher strength-to-weight ratios.

10.55 By incorporating small amounts of blowing agent, it is possible to produce polymer fibers with gas cores. List some applications for such fibers.

By the student. Examples include applications where weight is a primary concern, such as aerospace structures. Also, such a structure is very common in foams, and the typical applications are for flotation devices (life savers, surfboards, etc), or thermal applications where the gas cores act as an effective insulators (coffee cups, thermos, etc.). If woven into a fabric, it can be an effective insulator for winter clothing.

10.56 With injection-molding operations, it is common practice to remove the part from its runner and then to place the runner into a shredder and recycle into pellets. List the concerns you would have in using such recycled pellets as opposed to so-called virgin pellets.

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By the student. Consider the following concerns:

(a) The polymer may become chemically contaminated by tramp oils or parting agents on the die;

(b) Wear particles from the shredder may contaminate the polymer;

(c) The polymer may be chemically degraded from the heating and cooling cycles encountered in injection molding;

(d) The molecular weight of the shredded polymer may be much lower than that for the original polymer, so that the mechanical properties of the recycled stock can be inferior.

10.57 What characteristics make polymers attractive for applications such as gears? What characteristics would be drawbacks for such applications?

By the student. Students should be encouraged to develop answers that rely on their personal experience. The advantages include (a) the low friction of polymers, even when not lubricated), (b) wear resistance, (c) good damping characteristics, so that sound and impact forces are not as severe with plastic gears), and (d) manufacturing characteristics that allow the production of tooth profiles with superior surface finish (see Section 8.10.7). The main drawbacks to polymer gears are associated with low stiffness, especially at elevated temperature, and lower strength than metals (so the loads that can be transferred for an equivalent sized gear is much lower), but they would be suitable for motion translation.

10.58 Can polymers be used to conduct electricity? Explain, giving several examples.

Recall that polymers can be made to conduct electricity (see Section 10.7.2), such as polyacetylene, polyaniline, and polythiophene. Other polymers can be made more conductive by doping them with metal particles or whiskers. If continuous wire reinforcement is present, the polymer can be directionally conductive. It can also be conductive in a plane if a mesh reinforcement is used. An electroless nickel plating (p. 160) of a polymer part can also make it conductive. The students should comment further on this topic.

10.59 Why is there so much variation in the stiffness of polymers? What is its engineering significance?

By the student. Table 10.1 on p. 585 shows a wide range of stiffness; note, for example, that for polyethylene the change can be 1400%. This is mainly due to the widely varying degree of polymerization and crystallinity, and the number of crosslinks, if any, present, as well as the important effects of the reinforcements. Stiffness will increase with any of these variables.

10.60 Explain why thermoplastics are easier to recycle than thermosets.

If a polymer's chemistry can be identified, then a polymer product can be cut into small pieces (such as pellets or particles) and fabricated as is done with so-called virgin thermoplastics. There is some degradation of mechanical properties and a measurable loss of molecular weight, but if properly sorted (see top of p. 607), these drawbacks can be minimized. It is difficult to recycle thermosets because it is impossible to break down a thermosetting resin into its mer components. Thus, the manufacturing strategies for the original polymer and for its recycled counterparts have to be different. Furthermore, thermosets cannot be melted, or chopped up as would thermoplastics.

10.61 Describe how shrink-wrap works.

Shrink wrap consists of branched thermoplastics. When deformed above their glass-transition temperature, the branches attain a preferred orientation, similar to the effect of combing hair. The plastic is then quickly lowered in temperature, preventing stress relaxation. When the sheet is then wrapped around an object (including food products) and then heated, the stresses are relieved and the plastic sheet or film shrinks around the object.

10.62 List the characteristics required of a polymer for the following applications: (a) a total hip replacement insert, (b) a golf ball, (c) an automotive dashboard, (d) clothing, and (e) a child's doll.

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By the student. Consider, for example, the following:

(a) Some of the characteristics required for a polymer insert in a total hip replacement are that it be biocompatible; not dissolve or warp in the presence of bodily fluids; support the loads developed during normal walking, sitting, and standing; not wear excessively; and provide low friction. Cost is not as imperative as other applications, given the high cost of surgery for hip replacements.

(b) For a golf ball, abrasion resistance is important, as well as impact strength and toughness. The polymer needs to have a stiffness consistent with typical golf balls, and it must be coatable, so that it can be made into a bright color. Cost is also important.

(c) An automobile-dashboard polymer needs to be formable into the desired (and quite demanding) shapes. It also has to be available in a range of desired colors, and should have acceptable manufacturing cost.

(d) The polymer in clothing needs to be produced into fibers and in continuous lengths. The fibers must be sufficiently flexible so that they can be woven into cloth and withstand normal wear and tear. The polymer must have low elastic modulus but sufficient strength so that the cloth feels soft but doesn't tear easily. It must also be inexpensive.

(e) A child's doll must be non-toxic, and should be soft but tough so that the child cannot break off a piece of the doll and thus becoming a choking hazard. The polymer should be easy to decorate and cleanable.

10.63 How can you tell whether a part is made of a thermoplastic or a thermoset? Explain.

By the student. There are several nondestructive and destructive tests that can be performed. For example, tension tests will demonstrate the difference: a pronounced plasticity is indicative of a thermoplastic. Exposure to high temperatures is another test: the presence of a glass-transition temperature is indicative of a thermoplastic. The shape of the part is often a clue; for example, thin films must be made of thermoplastics because they are blown from extruded tubing.

10.64 Describe the features of an extruder screw and comment on their specific functions.

By the student. A typical extruder is shown in Figs. 10.22 and 10.23 on p. 620. The three principal features of the screw shown are:

- Feed section: In this region, the screw is intended to entrain powder or pellets from the hopper; as a result, the flight spacing and depth is larger than elsewhere on the screw.
- Melt section: In the melt section, the flight depth is very low and the plastic is melted against the hot barrel; also, gases that are entrained in the feed section are vented.
- Metering section: This region produced the pressure and flow rate needed for the extrusion operation.

Note that screws are designed for particular polymers, so the feed, melt, and metering sections are polymer-specific. Also, some extruders use two screws to increase the internal shearing and mixing of the polymer.

10.65 An injection-molded nylon gear is found to contain small pores. It is recommended that the material be dried before molding it. Explain why drying will solve this problem.

The probable reason is that the porosity is due to entrapped moisture in the material. Recall also that nylon absorbs water (*hygroscopy*; see top of p. 600), thus drying will alleviate this problem.

10.66 What determines the cycle time for (a) injection molding, (b) thermoforming, and (c) compression molding?

The cycle time for injection molding is determined by several factors, including:

- Material: Thermoplastics require much less time than thermosets, and certain thermoplastics will require less time to cool and solidify than will others (i.e., different thermal properties).

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- Part shape: If the part has a high surface area-to-volume, it will cool rapidly.
- Initial temperature: If a polymer is injected at a temperature much above its solidification temperature, it will require more time to cool.

The considerations for thermoforming and compression molding are similar. The students are encouraged to analyze and elaborate further on this subject.

10.67 Does the pull-in defect (sink marks) shown in Fig. 10.57 also occur in metal forming and casting processes? Explain.

The type of defect shown in Fig. 10.57 also occurs in metal forming (because of the flow of the material into the die cavity) and casting processes (because of excessive, localized surface shrinkage during solidification and cooling in the mold). This is described in various handbooks, but it should be noted that sink marks is a terminology restricted to polymer parts. For example, in Bralla, J.G., *Design for Manufacturability Handbook*, 2nd. ed., pp. 5.51, the sink marks are referred to as dishing for investment casting, and on p. 5.64 the same features are referred to as shrink marks.

10.68 List the differences between the barrel section of an extruder and that on an injection-molding machine.

By the student. Some of the basic differences between an extruder and an injection-molding machine barrel are:

- Extruders involve more heating from the heating elements and less from friction, so there will be more (or larger capacity) heating elements and temperature sensors in an extruder barrel.
- Extruders do not utilize torpedoes or reciprocating screws.
- Extruders may use multiple screws to improve mixing in the barrel.

10.69 Identify processes that are suitable for making small production runs of plastic parts, such as quantities of 100 or fewer. Explain.

By the student. Refer to Table 10.9 on p. 658 and note that low quantities involve processes in which tooling costs must be kept low. Thus, the most suitable processes would be casting and machining (because of the readily available and versatile machine tools). However, rapid prototyping operations can also be used directly if the quantities are sufficiently small and part characteristics are acceptable. Also, tooling can be produced using the methods described in Section 10.12.6 to render processes such as injection molding viable for small production runs. Note, however, that these tools are not suitable for large production runs.

10.70 Review the Case Study to this chapter and explain why aligners cannot be made directly by rapid prototyping operations.

As described in the Case Study on p. 658, the polymers in stereolithography have a yellow tint, which is objectionable for cosmetic reasons. However, there are some clear polymers now available (see WaterShed 11120 in Table 10.8 on p. 646), but it is difficult to fully cure the monomer, making the aligners develop an unpleasant taste.

10.71 Explain why rapid prototyping approaches are not suitable for large production runs.

The main reasons are the long times required for producing parts (2 hours or so for a small part is rapid when only one part is required. Two hours per part is unacceptably long for a million parts. Recall also that rapid prototyping operations can be very demanding and require high-quality materials that have high cost associated with them.

10.72 List and explain methods for quickly manufacturing tooling for injection molding.

This topic is discussed in Section 10.12.6. Depending on the material, the following are options:

- A mold can be directly produced with a rapid prototyping operation if the polymer to be injection molded has a lower melting temperature than the mold material.
- An RTV molding/urethane casting operation can be employed (see p. 653), using a rapid prototyped pattern.

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- ACES injection molding uses a rapid-prototyped tooling shell backed with a low-melting-point metal.
- Sprayed metal tooling can produce a shell from a rapid-prototyped pattern. The shell is backed with an epoxy or aluminum-filled epoxy, for strength and to remove heat from injection molding.
- The Keltool process (see p. 654) can be used, using an RTV mold, filled with powdered A6 tool steel infiltrated with copper.

10.73 Careful analysis of a rapid-prototyped part indicates that it is made up of layers with a white filament outline visible on each layer. Is the material a thermoset or a thermoplastic? Explain.

The presence of the filament outline suggests that the material was produced in fused-deposition modeling (Section 10.12.3). This process requires adjacent layers to fuse after being extruded. Extrusion and bonding is obviously possible with thermoplastics but very difficult for a thermoset.

10.74 List the advantages of using a room-temperature vulcanized (RTV) rubber mold in injection molding.

The advantages include the following:

- The tooling cost is low.
- Very detailed part geometry can be incorporated into the RTV mold.
- The mold is flexible, so that it can be peeled off of parts; thus, draft angles and other design considerations for metallic tooling can be relaxed.
- The RTV mold can be produced with the aid of rapid prototyping operations so that the mold is quickly produced.

Note that there are also disadvantages to this method, mainly the limited tool life.

10.75 What are the similarities and differences between stereolithography and cyberjet?

As seen in Table 10.7 on p. 646, note that (a) both processes rely on the same layer-creation technique, namely liquid-layer curing, (b) both use a principle of using a photopolymer to create a thermoset part, and (c) both have comparable materials, with similar characteristics of strength, cost, and appearance.

10.76 Explain how color can be incorporated into rapid-prototyped components.

The following methods are the most straightforward:

- The ZCorp (see Fig. 10.52 on p. 651) versions of three-dimensional printing machines incorporate colored binders, so that full-color prototypes can be produced directly.
- FDM machines usually have two heads, so that two colors can be extruded as desired.
- Otherwise, color is most easily incorporated by painting the prototyped part.

Problems

10.77 Calculate the areas under the stress-strain curve (toughness) for the material in Fig. 10.9, plot them as a function of temperature, and describe your observations.

Temperature (°C)	Toughess (MJ/m^3)
-25	140
0	635
25	760
50	730
65	520
80	500

The area under the curves is estimated by adding the area under the initial elastic region to that in the flat regions. The results are as follows:

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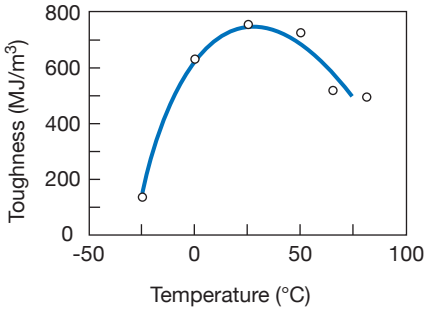


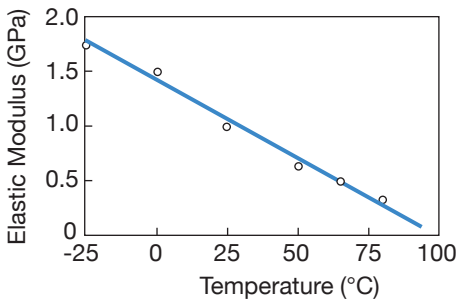
Note that there is an optimum temperature for maximum toughness.

10.78 Note in Fig. 10.9 that, as expected, the elastic modulus of the polymer decreases as temperature increases. Using the stress-strain curves given in the figure, make a plot of the modulus of elasticity versus temperature.

Note that all curves start at the origin, and undergo a transition from linear elastic behavior to plastic behavior at a strain of approximately 4%. We can therefore estimate the elastic modulus from the slope of the curves up to 4% strain. The following table can be constructed:

Temperature (°C)	Stress at 4% strain (MPa)	Elastic modulus (GPa)
-25	70	1.75
0	60	1.5
25	40	1.0
50	25	0.625
65	20	0.50
80	13	0.325

The resulting plot is as follows:



10.79 Calculate the percentage increase in mechanical properties of reinforced nylon from the data shown in Fig. 10.19.

The following data is obtained from Fig. 10.19 on p. 615, with the last column calculated from the data. Also, note that the flexural modulus of nylon has been obtained from Table 10.1 on p. 585 as 1.4 GPa.

Property	Temperature 0%	Temperature 40%	% Increase
Tensile strength	100	200[a]	100
(MPa)		250[b,c]	150
Impact energy	70	150[a]	114
(J/m)		295[b]	321
		80[c]	14
Flexural modulus	1.4	12[a,b]	757
(GPa)		25[c]	1686
Flexural strength	150	300[a]	100
(MPa)		330[b]	120
		350[c]	133

Notes: 1. short glass; 2. long glass; 3. carbon.

10.80 A rectangular cantilever beam 75-mm high, 25-mm wide, and 1-m long is subjected to a concentrated force of 100 N at its end. Select two different unreinforced and reinforced materials from Table 10.1, and calculate the maximum deflection of the beam. Then select aluminum and steel, and for the same beam dimensions, calculate the maximum deflection. Compare the results.

This is a simple mechanics of solids problem in which the governing equation for the deflection, d, of a cantilever beam with a concentrated load of P (=100 N) at the end is

$$d = \frac{PL^3}{3EI}$$

where L is the beam length (1 m), E the elastic modulus of the material chosen from Table 10.1, and I is the moment of inertia, i.e.,

$$I = \frac{bh^3}{12} = \frac{(25)(75)^3}{12} = 8.79 \times 10^5 \text{ mm}^4$$

Substituting for moment of inertia, load, and

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length gives the deflection as

$$\begin{aligned} d &= \frac{PL^3}{3EI} \\ &= \frac{(100\text{ N})(1\text{ m})^3}{3\,(8.79\times 10^5\text{ mm}^4)}\frac{1}{E} \\ &= \frac{3.792\times 10^7\text{ N/m}}{E} \end{aligned}$$

Thus, the higher the elastic modulus, the smaller the deflection of the beam. Examples of the results are as follows:

Material	E (GPa)	d (mm)
Aluminum	70[a]	0.542
Steel	200[a]	0.190
ABS, nylon	1.4	27.1
Polyesters	2.0	19.0
Polystyrene	2.7	14.0

Note: [a] From Table 2.1.

10.81 In Sections 10.5 and 10.6, we listed several plastics and their applications. Rearrange this information, respectively, by making a table of products and the type of plastics that can be used to make the products.

The following is an example of an acceptable answer to this problem. Note that there are many approaches and part classifications that could be used, and the information in the textbook could be supplemented with Internet searches. Also, many more products could be listed if desired.

Product	Polymers
Bearings	Acetals, fluorocarbons, nylon, polyimides
Gears	Acetals, nylon, polyester, polyimides
Cams	Acetals, polyester
Lenses	Acrylics, cellulosics, polycarbonates
Furniture	Acrylics, polystyrene
Housings	Acetals, ABS, polypropylene, polysulfone, aminos
Low wear	Nylon, polyethylene
Guards	Cellulosics, polycarbonates
Pipes	ABS, cellulosics, polypropylene, PVC
Toys	Cellulosics, polyethylene, polystyrene
Electrical insulation	Fluorocarbons, nylon, polycarbonate, polypropylene, polysulfone, PVC
Food contact	Polycarbonate, polypropylene, polystyrenes, melamine
Gaskets	Fluorocarbons, PVC, silicones

10.82 Determine the dimensions of a tubular steel drive shaft for a typical automobile. If you now replace this shaft with shafts made of unreinforced and reinforced plastic, respectively, what should be the shaft's new dimensions to transmit the same torque for each case? Choose the materials from Table 10.1, and assume a Poisson's ratio of 0.4.

Note that the answers will vary widely depending on the shaft dimensions. However,

$$J = \frac{\pi}{32}\left(D_o^4 - D_i^4\right)$$

The shear stress under pure torsion for a tubular shaft is given by

$$\tau = \frac{T(D_o/2)}{J} = \frac{16TD_o}{\pi\left(D_o^4 - D_i^4\right)}$$

Therefore, the torque that can be carried by the shaft at the shear yield stress of the material is

$$T = \frac{k\pi\left(D_o^4 - D_i^4\right)}{16D_o}$$

Since steel has a higher shear stress than reinforced polymers, the tube dimensions will have to be modified in order to accommodate the

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same torque. Using an s subscript for steel and p for polymer, it can be seen that

$$\frac{k_s\pi\left(D_{os}^4 - D_{is}^4\right)}{16D_{os}} = \frac{k_p\pi\left(D_{op}^4 - D_{ip}^4\right)}{16D_{op}}$$

or

$$\frac{k_s}{k_p} = \frac{D_{op}^{-1}\left(D_{op}^4 - D_{ip}^4\right)}{D_{os}^{-1}\left(D_{os}^4 - D_{is}^4\right)}$$

As an example, compare a low-carbon steel (UTS=395 MPa) to reinforced ABS, with a UTS of 100 MPa. For solid shafts, ($D_{is} = D_{ip} = 0$), the required outer diameter of the ABS shaft is

$$\frac{395}{100} = \frac{(1/D_{op})\,D_{op}^4}{(1/D_{op})\,D_{op}^4}$$

or

$$D_{op} = (3.95)^{1/3}D_{os} = 1.58D_{os}$$

10.83 Calculate the average increase in the properties of the plastics listed in Table 10.1 as a result of their reinforcement, and describe your observations.

The results are given in the following table.

Material	Prop-property[a]	Unrein-forced (ave)	Rein-forced (ave)	Average increase %
ABS	UTS	41.5	100	59
	E	2.1	7.5	54
Acetal	UTS	62.5	135	73
	E	2.45	10.0	75.5
Epoxy	UTS	87.5	735	648
	E	10.2	36.5	263
Nylon	UTS	69	140	71
	E	2.1	6.0	39
Polycarb-onate	UTS	62.5	110	48
	E	2.1	6.0	39
Polyester	UTS	55	135	80
	E	2.0	10.2	82
Polyprop-ylene	UTS	27.5	70	43
	E	0.95	4.75	38

Note: (a) UTS in MPa, E in GPa

10.84 In Example 10.4, what would be the percentage of the load supported by the fibers if their strength is 1250 MPa and the matrix strength is 240 MPa? What if the strength is unaffected, but the elastic modulus of the fiber is 600 GPa while the matrix is 50 GPa?

A review of the calculations in Example 10.4 on p. 617 indicates that the strength of the materials involved does not influence the results. Since the problem refers only to changes in strength, it is assumed that the moduli of elasticity are the same as in the original example.

If the strength is unaffected, but the elastic moduli are changed, there will be an effect on the load supported by the fibers. The percentage of the load supported by the fibers can then be calculated as follows:

$$E_c = (0.2)(600) + (1 - 0.2)(50) = 120 + 40$$

or $E_c = 160$ GPa. Also,

$$\frac{F_f}{F_m} = \frac{(0.20)(600)}{(0.8)(50)} = \frac{120}{40} = 3$$

or

$$F_c = F_f + F_f/3 = 1.33F_f$$

and

$$F_f = 0.75F_c$$

Thus, the fibers support 75% of the load in this composite material. As expected, this percentage is higher than the 43% in the sample calculations given in Example 10.4.

10.85 Estimate the die clamping force required for injection molding 10 identical 1.5-in.-diameter disks in one die. Include the runners of appropriate length and diameter.

Note that this question can be answered in several ways, and that the layout is somewhat arbitrary. In fact, the force could conceivably be based on the thickness of the disc, but this would be a much more difficult cavity to machine into a die, and a far more difficult part to eject. Instead, we will use central sprues with runners to feed two rows of five discs each. Using 0.25-in. diameter runners, their contribution to the area is

$$A_{\text{runners}} = 2(0.25\text{ in.})(10\text{ in}) = 5\text{ in}^2$$

Note that we have allowed some extra space to have clearance between the disks. The total disk surface area is then

$$A_{\text{discs}} = 10\left(\frac{\pi d^2}{4}\right) = 10\left(\frac{\pi(1.5\text{ in.})^2}{4}\right)$$

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or $A_{\text{discs}} = 17.7$ in^2. Therefore, the total surface area of the mold is about 23 in^2. As stated in Section 10.10.2, injection pressures range from 10,000 to 30,000 psi. Therefore, the clamping force will range from 230,000 (115) to 690,000 lb (345 tons).

10.86 A two-liter plastic beverage bottle is made from a parison with the same diameter as the threaded neck of the bottle and has a length of 5 in. Assuming uniform deformation during blow molding, estimate the wall thickness of the tubular section.

This problem will use typical values for two-liter bottle dimensions, but small deviations from these numbers, and hence the answer, are likely. If open-ended problems are not desirable, the student can be asked to use $L = 9$ in., $D = 4.25$ in., and $t = 0.015$ in. for the finished bottle, with a 1.125 in. diameter neck. These are reasonable values that are used in this solution.

The volume of the plastic material is estimated as

$$V = \pi DLt = \pi(4.25)(9)(0.015) = 1.8 \text{ in}^3$$

As stated in the problem, the parison is a tubular piece 5 in. long, and its diameter is the same as the threaded neck of a two-liter bottle, i.e., about $1\frac{1}{8}$ in., as measured. Let's assume that, as in metals, the volume of the material does not change during processing (although this is not a good assumption because of significant density variations in polymers due to changes in the free space or free volume in their molecular structure). Assuming volume constancy as an approximation, the thickness t_p of the parison is calculated as

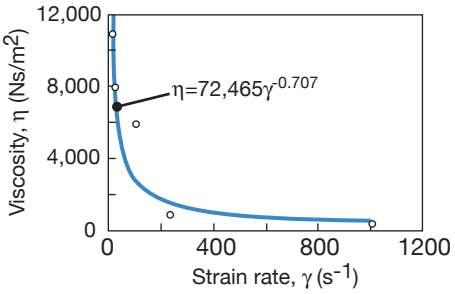
$$1.8 = \pi(1.125)t_p(5) \quad \rightarrow \quad t_p = 0.10 \text{ in.}$$

10.87 Estimate the consistency index and power-law index for the polymers in Fig. 10.12.

The solution requires consideration of the data given in Fig. 10.12b on p. 597. As an example, consider rigid PVC at 190°C. The following data is interpolated from the curve:

Strain rate γ (s^{-1})	Viscosity (Ns/m^2)
10	11,000
23	8000
100	6000
230	1000
1000	500

The plot is constructed from this data as follows:



A curve fit of the form of $\eta = A\gamma^{1-n}$ is fit to the data, suggesting that the consistency index is $A = 72,465$ Ns/m^2, and that the power law index is

$$1 - n = -0.707 \quad \rightarrow \quad n = 1.707$$

10.88 An extruder has a barrel diameter of 100 mm. The screw rotates at 100 rpm, has a channel depth of 6 mm, and a flight angle of 17.5°. What is the highest flow rate of polypropylene that can be achieved?

The highest flow rate is if there is zero pressure at the end of the barrel, and then we have pure drag flow, given by Eq. (10.20) as

$$Q_d = \frac{\pi^2 D^2 H N \sin\theta \cos\theta}{2}$$

Using $D = 100$ mm, $H = 6$ mm, $N = 100$ rpm and $\theta = 17.5°$ gives

$$Q_d = \frac{\pi^2(100)^2(6)(100)\sin 17.5° \cos 17.5°}{2}$$

or $Q_d = 8.49 \times 10^6$ mm^3/min $= 141{,}500$ mm^3/sec.

10.89 The extruder in Problem 10.88 has a pumping section that is 2.5 m long and is used to extrude round polyethylene solid rod. The die has a land of 1 mm and a diameter of 5 mm. If the polyethylene is at a mean temperature of

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250°C, what is the flow rate through the die? What if the die diameter is 10 mm?

The extruder characteristic is given by Eq. (10.23) on p. 621 as

$$Q = \frac{\pi^2 D^2 H N \sin\theta\cos\theta}{2} - \frac{\pi D H^3 \sin^2\theta}{12\eta l} p$$

For polyethylene at 250°C, the viscosity η is about 80 Ns/m^2, as obtained from Fig. 10.12. Also, from the statement of Problem 10.88, we know that $D = 100$ mm, $H = 6$ mm, $N = 100$ rpm, and $\theta = 17.5°$; l is given as 2.5 m. Therefore, the extruder characteristic is

$$Q = \frac{\pi^2(0.100)^2(0.006)(100)\sin 17.5°\cos 17.5°}{2} - \frac{\pi(0.100)(0.006)^3\sin^2 17.5°}{12\,(80)\,(3)} p$$

or

$$Q = 0.00849 \text{ m}^3/\text{min} - \left(2.13 \times 10^{-12} \text{ m}^5/\text{N-min}\right) p$$

For this die, the die characteristic is given by Eq. (10.25) on p. 621, where K is evaluated from Eq. (10.26) as

$$K = \frac{\pi D_d^4}{128\eta l_d} = \frac{\pi(0.005)^4}{128(80)(0.001)}$$

or $K = 1.15 \times 10^{-10}$ m^5/N-min. Therefore, the die characteristic is given by

$$Q = Kp = \left(1.15 \times 10^{-10} \text{ m}^5/\text{N-min}\right) p$$

We now have two equations and two unknowns; these are solved as $p = 72.5$ MPa and $Q = 0.00833$ m^3/min.

If the die has a diameter of 10 mm, then

$$K = \frac{\pi D_d^4}{128\eta l_d} = \frac{\pi(0.010)^4}{128(80)(0.001)}$$

or $K = 3.07 \times 10^{-9}$, and the simultaneous equations then yield $Q = 0.00848$ m^3/min and $p = 2.7$ MPa.

10.90 An extruder has a barrel diameter of 4 in., a channel depth of 0.25 in., a flight angle of 18°, and a pumping zone that is 6 ft long. It is used to pump a plastic with a viscosity of 100×10^{-4} lb-s/in^2. If the die characteristic is experimentally determined as $Q_x = (0.00210 \text{ in}^5/\text{lb-s})p$, what screw speed is required to achieve a flow rate of 7 in^3/s from the extruder?

The pressure at the die can be determined from the die characteristic and the required flow rate, using Eq. (10.25):

$$Q = 7 \text{ in}^3/\text{s} = Kp = (0.00210 \text{ in}^5/\text{lb-s})p$$

Solving for p,

$$p = \frac{7}{0.00210} = 3.333 \text{ ksi}$$

From Eq. (10.23), the extruder characteristic is

$$Q = \frac{\pi^2 D^2 H N \sin\theta\cos\theta}{2} - \frac{\pi D H^3 \sin^2\theta}{12\eta l} p$$

Solving for N,

$$N = \left[\frac{2}{\pi^2 D^2 H \sin\theta\cos\theta}\right]\left[Q + \frac{\pi D H^3 \sin^2\theta}{12\eta l} p\right]$$

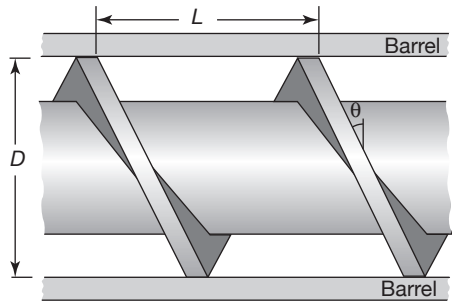
or

$$N = \left[\frac{2}{\pi^2(4)^2(0.25)\sin 18°\cos 18°}\right] \times \left[7 + \frac{\pi(4)(0.25)^3\sin^2 18°}{12\,(100 \times 10^{-4})\,(72)}(3333)\right]$$

or $N = 2.45$ rev/s, or 147 rpm.

10.91 What flight angle should be used on a screw so that a flight translates a distance equal to the barrel diameter with every revolution?

Refer to the following figure:



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The relationship between the screw angle, θ, the lead, L, and diameter, D, can be best seen by unwrapping a revolution of the screw. This gives

$$\theta = \tan^{-1}\left(\frac{L}{\pi D}\right)$$

For $L = D$, we have

$$\theta = \tan^{-1}\left(\frac{D}{\pi D}\right) = \tan^{-1}\left(\frac{1}{\pi}\right)$$

Therefore, $\theta = 17.6°$.

10.92 For a laser providing 10 kJ of energy to a spot with diameter of 0.25 mm, determine the cure depth and the cured line width in stereolithography. Use $E_c = 6.36 \times 10^{10}$ J/m^2 and $D_p = 100$ μm.

The exposure at the surface of the material is given by

$$E_o = \frac{10 \text{ kJ}}{\frac{\pi}{4}(0.25 \text{ mm})^2} = 2.04 \times 10^{11} \text{ J/m}^2$$

For $D_p = 100$ μm=0.1 mm, Eq. (10.29) on p. 644 gives the cure depth as

$$\begin{aligned} C_d &= D_p \ln\left(\frac{E_o}{E_c}\right) \\ &= (0.1 \text{ mm}) \ln\left(\frac{2.04 \times 10^{11}}{6.36 \times 10^{10}}\right) \\ &= 0.116 \text{ mm} \end{aligned}$$

Therefore, the linewidth is given by Eq. (10.30) as

$$L_w = B\sqrt{\frac{C_d}{2D_p}} = (0.25 \text{ mm})\sqrt{\frac{0.116}{2(0.1)}}$$

or $L_w = 0.19$ mm. Note that this is smaller than the laser diameter of 0.25 mm.

10.93 For the stereolithography system described in Problem 10.92, estimate the time required to cure a layer defined by a 40-mm circle if adjacent lines overlap each other by 10% and the power available is 10 MW.

The following solution uses the results from the solution to Problem 10.92. If the linewidth is 0.19 mm, the allowable linewidth to incorporate a 10% overlap is 0.171 mm. A 40-mm diameter circle has an area of 1257 mm^2; thus, a laser would have to travel a total distance of 7.35 m using the 0.171 mm linewidth. Since the required energy is 10 kJ for a length of 0.25 mm and the power available is 10 MW, the spot velocity can be obtained from

$$10 \text{ MW} = \frac{10 \text{ kJ}}{0.25 \text{ mm}} v$$

Solving for the velocity yields $v = 0.25$ m/s. Therefore, the laser will take 7.35/0.25=29.4 s to cure the circle.

10.94 The extruder head in a fused-deposition-modeling setup has a diameter of 1 mm (0.04 in.) and produces layers that are 0.25 mm (0.01 in.) thick. If the velocities of the extruder head and polymer extrudate are both 50 mm/s, estimate the production time for generating a 50-mm (2-in.) solid cube. Assume that there is a 15-s delay between layers as the extruder head is moved over a wire brush for cleaning.

Note that although the calculations are given below, in practice, the rapid-prototyping software can easily make such a calculation. Since the thickness of the cube is 50 mm and the layers are 0.25 mm thick, there are 200 layers, for a total inactive' time of (200)(15 s)=3000 s. Note also that the cross section of the extruded filament in this case is highly elliptical, and thus its shape is not easily determined from the information given in the problem statement. However, the polymer extrudate speed is given as 50 mm/s and the orifice diameter is 1 mm, hence the volume flow rate is

$$\begin{aligned} Q &= vA = (50 \text{ mm/s})\left[\frac{\pi}{4}(1 \text{ mm})^2\right] \\ &= 39.27 \text{ mm}^3/\text{s} \end{aligned}$$

The cube has a volume of (50)(50)(50)=125,000 mm^3 and the time required to extrude this volume is 125,000/39.27=3180 s. Hence, the total production time is 3180 s + 3000 s = 6180 s = 1.7 hrs. Note that this estimate does not include any porosity, and it assumes that extrusion is continuous. In practice, however, the extruder has to periodically pick up and move to a new location in a layer.

10.95 Using the data for Problem 10.94 and assuming that the porosity of the support material is

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50%, calculate the production rate for making a 100-mm (4-in.) high cup with an outside diameter of 88 mm (3.5 in.) and wall thickness of 6 mm (0.25 in.). Consider both the case with the closed-end (a) down and (b) up.

(a) (a) Closed-end down. No support material is needed. There are 400 layers, so the inactive' time is 6000 s. The cup wall volume is

$$\begin{aligned} V &= \frac{\pi}{4}d^2t + \pi dht \\ &= \frac{\pi}{4}(88\text{ mm})^2(6\text{ mm}) \\ &\quad +\pi(88\text{ mm})(100\text{ mm})(6\text{ mm}) \end{aligned}$$

or $V = 202,000\text{ mm}^3$. It takes $202,000/39.27 = 5140$ s to extrude; the total time is $6000 + 5140 = 11,140$ s $= 3.1$ hrs.

(b) (b) Closed-end up. In addition to the wall, the interior must now be filled with support for the closed-end on top. The volume of the cup is

$$\begin{aligned} V &= \frac{\pi}{4}d^2h \\ &= \frac{\pi}{4}(88\text{ mm})^2(100\text{ mm}) \\ &= 608,000\text{ mm}^3 \end{aligned}$$

Since the support material has a porosity of 50%, the time required to extrude the support material is $t = 304,000/39.27 = 7740$ s $= 2.2$ hrs. Therefore, the total time for producing the part and the support is $3.1 + 2.2 = 5.3$ hrs.

10.96 What would the answer to Example 10.5 be if the nylon has a power law viscosity with $n = 0.5$? What if $n = 0.2$?

Since the nylon has a power law viscosity, then Eq. (10.24) on p. 621 has to be used for the extruder characteristic, instead of Eq. (10.23). The extruder characteristic is thus given by

$$\begin{aligned} Q &= \left(\frac{4+n}{10}\right)\left(\pi^2 HD^2 N\sin\theta\cos\theta\right) \\ &\quad -\frac{p\pi DH^3\sin^2\theta}{(1+2n)4\eta} \\ &= \pi^2\left(\frac{4+0.5}{10}\right) \\ &\quad \times\left[(0.007)(0.05)^2(0.833)\sin 20^\circ\cos 20^\circ\right] \\ &\quad -\frac{\pi(0.05)(0.007)^3\sin^2 20^\circ}{[1+2(0.5)](4)(300)}p \\ &= 2.08\times 10^{-5} - \left(2.62\times 10^{-12}\right)p \end{aligned}$$

If the same die characteristic can be used, then there are two equations and two unknowns. This results in $p = 4.01$ MPa and $Q = 1.03 \times 10^{-5}$ m^3/s.

Using the more realistic value of $n = 0.2$, the extruder characteristics becomes

$$\begin{aligned} Q &= \left(\frac{4+n}{10}\right)\left(\pi^2 HD^2 N\sin\theta\cos\theta\right) \\ &\quad -\frac{p\pi DH^3\sin^2\theta}{(1-2n)4\eta} \\ &= \pi^2\left(\frac{4+0.2}{10}\right) \\ &\quad \times\left[(0.007)(0.05)^2(0.833)\sin 20^\circ\cos 20^\circ\right] \\ &\quad -\frac{\pi(0.05)(0.007)^3\sin^2 20^\circ}{[1+2(0.2)](4)(300)}p \\ &= 1.94\times 10^{-5} - \left(3.75\times 10^{-12}\right)p \end{aligned}$$

If the same die characteristic can be used, there are two equations and two unknowns. This results in $p = 3.07$ MPa and $Q = 7.87 \times 10^{-6}$ m^3/s.

10.97 Referring to Fig. 10.7, plot the relaxation curves (i.e., the stress as a function of time) if a unit strain is applied at time $t = t_o$.

Consider first the simple spring and dashpot models shown in parts (a) and (b) of the figure. If a unit strain is applied to a spring, the force developed is $F = k$, where k is the stiffness of the spring. This force will be maintained and will not change as long as the deformation is maintained. For the dashpot model, a unit change in strain causes an infinite force, but the force quickly drops to zero as the strain is maintained, because the strain rate is zero. Thus, the relaxation curve for a spring is a constant,

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and for the dashpot, it is a multiple of the *Dirac delta function*.

For the Maxwell model, when the unit strain is applied, the spring immediately stretches since the dashpot has a high resistance to deformation. As the deformation is held, the load is transferred from the spring. The relaxation function is given by

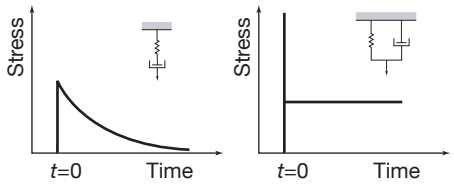
$$\sigma(t) = ke^{-(k/\eta)t}$$

where k is the spring stiffness and η is the coefficient of viscosity for the dashpot.

For the Voigt model, the application of a unit strain causes the dashpot to develop infinite force. After $t = 0$, the strain rate is zero and the dashpot develops no force, so that the force is that generated by the spring under a unit strain. The relaxation curve for the Voigt model is given by

$$\sigma(t) = \eta\delta(t) + k$$

where δ is the Dirac delta function. These curves are plotted below:



10.98 Derive a general expression for the coefficient of thermal expansion for a continuous fiber-reinforced composite in the fiber direction.

Note that, in this case, a temperature rise leads to a thermal expansion of the composite, so that its deflection can be written as

$$\delta_c = \alpha_c \Delta t l$$

where α is the coefficient of thermal expansion and a c subscript indicates a property of the composite. For the fiber and matrix, there will be an internal stress developed, unless the coefficients of thermal expansion are the same for the fiber and the matrix. If not, then an internal stress is developed in order to ensure that the fiber and matrix undergo the same deformation as the composite. Assume that the fiber has a higher coefficient of thermal expansion than the matrix, so that the fibers are compressed by the internal stress and the matrix is loaded in tension. Therefore, the deformation of the fibers is given by

$$\delta_f = \alpha_f \Delta t l - \frac{\sigma_f}{E_f} l$$

and for the matrix:

$$\delta_m = \alpha_m \Delta t l + \frac{\sigma_m}{E_m} l$$

Since the deformations have to be equal, we have

$$\alpha_f \Delta t l - \frac{\sigma_f}{E_f} l = \alpha_m \Delta t l + \frac{\sigma_m}{E_m} l$$

or

$$(\alpha_f - \alpha_m)\Delta t = \frac{\sigma_f}{E_f} + \frac{\sigma_m}{E_m}$$

Note that the internal forces must balance each other, so that

$$\sigma_f A_f = -\sigma_m A_m$$

where the minus sign indicates that the fibers are loaded in compression and the matrix in tension (or vice-versa). Thus,

$$\sigma_m = \frac{x}{1-x}\sigma_f$$

Substituting, we have

$$(\alpha_f - \alpha_m)\Delta t = \sigma_f \left[\frac{1}{E_f} + \frac{x}{(1-x)E_m}\right]$$

Solving for σ_f,

$$\sigma_f = \frac{(\alpha_f - \alpha_m)\Delta t}{\left[\frac{1}{E_f} + \frac{x}{(1-x)E_m}\right]}$$

Therefore, the fiber deformation becomes

$$\begin{aligned}\delta_f &= \alpha_f \Delta t l - \frac{(\alpha_f - \alpha_m)\Delta t}{E_f\left[\frac{1}{E_f} + \frac{x}{(1-x)E_m}\right]} l \\ &= \left\{\alpha_f - \frac{(\alpha_f - \alpha_m)}{E_f\left[\frac{1}{E_f} + \frac{x}{(1-x)E_m}\right]}\right\}\Delta t l\end{aligned}$$

Since this is the same as the deformation of the composite,

$$\alpha_c \Delta t l = \left\{\alpha_f - \frac{(\alpha_f - \alpha_m)}{\left[1 + \frac{x}{(1-x)}\frac{E_f}{E_m}\right]}\right\}\Delta t l$$

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or

$$\alpha_c = \alpha_f - \frac{(\alpha_f - \alpha_m)}{\left[1 + \frac{x}{(1-x)}\frac{E_f}{E_m}\right]}$$

10.99 Estimate the number of molecules in a typical automobile tire. Estimate the number of atoms.

An automobile tire is an example of a highly cross-linked network structure (see Fig. 10.3). In theory, a networked structure can continue indefinitely, so that an automobile tire could be considered as one giant molecule. In reality, there are probably a few thousand molecules.

Although tires come in a wide variety of sizes, consider a tire with 10 kg of rubber, produced from polybutadiene, $(C_4H_6)_n$. (Note that there is additional weight associated with the reinforcement and pigment in the tire.) The atomic weight of carbon is 12.011 and that of hydrogen is 1.0079, as obtained from a periodic table of elements. Thus, a polybutadiene mer has a molecular weight of 54.09. Therefore, a mole of such mers (or 10 moles of atoms) would weigh 54.09 grams. In a 20-kg tire, there are 20000/54.09 = 370 moles of butadiene mers, or 3700 moles of atoms. Since 1 mole $= 6.023 \times 10^{23}$, there are 2.23×10^{27} atoms in a tire.

10.100 Calculate the elastic modulus and percentage of load supported by fibers in a composite with an epoxy matrix (E = 10 GPa), with 20% fibers made of (a) high-modulus carbon and (b) Kevlar 29.

From Table 10.4 on p. 609, for high-modulus carbon, E = 415 GPa and for Kevlar 29, E = 62 GPa. For $x = 0.2$, Eq. (10.16) on p. 617 gives, for the high-modulus carbon,

$$\begin{aligned} E_c &= xE_f + (1-x)E_m \\ &= (0.2)(415 \text{ GPa}) + (1-0.2)(10 \text{ GPa}) \\ &= 91 \text{ GPa} \end{aligned}$$

The same calculation for Kevlar 29 gives E_c = 20.4 GPa. Using Eq. (10.15),

$$\frac{F_f}{F_m} = \frac{A_f E_f}{A_m E_m} = \frac{xAE_f}{(1-x)AE_m} = \frac{xE_f}{(1-x)E_m}$$

So that F_m is:

$$F_m = \left[\frac{(1-x)E_m}{xE_f}\right] F_f$$

Substituting into Eq. (10.12) yields

$$F_c = F_f + F_m = F_f + \left[\frac{(1-x)E_m}{xE_f}\right] F_f$$

or

$$F_c = \left[1 + \frac{(1-x)E_m}{xE_f}\right] F_f$$

For the high-modulus carbon reinforced epoxy composite,

$$F_c = \left[1 + \frac{(1-0.2)(10)}{(0.2)(415)}\right] F_f = 1.10F_f$$

or $F_f = 0.91F_c$. For the Kevlar fiber-reinforced composite,

$$F_c = \left[1 + \frac{(1-0.2)(10)}{(0.2)(62)}\right] F_f = 1.65F_f$$

or $F_f = 0.61F_c$.

10.101 Calculate the stress in the fibers and in the matrix for Problem 10.100. Assume that the cross-sectional area is 50 mm^2 and F_c = 2000 N.

Using the results for Problem 10.100, we note:

(a) For the high-modulus carbon fibers,

$$A_f = 0.2A_c = 0.2(50 \text{ mm}^2) = 10 \text{ mm}^2$$

$$F_f = 0.91F_c = 0.91(2000 \text{ N}) = 1820 \text{ N}$$

Therefore,

$$\sigma_f = \frac{1820 \text{ N}}{10 \text{ mm}^2} = 182MPa$$

Similarly, A_m = 40 mm^2, F_m = 180 N, and σ_m = 4.5 MPa.

(b) For the Kevlar 29 fibers,

$$A_f = 0.2A_c = 0.2(50 \text{ mm}^2) = 10 \text{ mm}^2$$

$$F_f = 0.61F_c = 0.61(2000 \text{ N}) = 1220 \text{ N}$$

Therefore,

$$\sigma_f = \frac{1220 \text{ N}}{10 \text{ mm}^2} = 122MPa$$

and for the matrix, A_m = 40 mm^2, F_m = 780 N, and σ_m = 19.5 MPa.

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10.102 Consider a composite consisting of reinforcing fibers with $E_f = 300$ GPa. If the allowable fiber stress is 200 MPa and the matrix strength is 50 MPa, what should be the matrix stiffness so that the fibers and matrix fail simultaneously?

From Eq. (10.15),

$$\frac{F_f}{F_m} = \frac{x}{1-x}\frac{E_f}{E_m} = \frac{x}{1-x}\frac{300}{E_m}$$

Since $F = \sigma A$,

$$\frac{F_f}{F_m} = \frac{\sigma_f A_f}{\sigma_m A_m} = \frac{200xA}{50(1-x)A} = \frac{x}{1-x}\frac{300}{E_m}$$

or

$$\frac{200}{50} = \frac{300}{E_m}$$

which is solved as $E_m = 75MPa$.

10.103 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare five quantitative problems and five qualitative questions, and supply the answers.

By the student. This is a challenging question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

DESIGN

10.104 Make a survey of the recent technical literature and present data indicating the effects of fiber length on such mechanical properties as the strength, elastic modulus, and impact energy of reinforced plastics.

By the student.

10.105 Discuss the design considerations involved in replacing a metal beverage container with a container made of plastic.

By the student. See also Question 10.40 which pertains to manufacturing considerations of beverage cans. This is an open-ended problem that can involve a wide variety of topics. Some of the major concerns are as follows. Note that the beverage can must be non-toxic and should have sufficient strength resist rupturing under internal pressure (which typically is on the order of about 120 psi) or buckling under a compressive load during stacking in stores. The can should maintain its properties, from low temperatures in the refrigerator to hot summer temperatures outside, especially under the sun in hot climates. Particularly important is the gas permeability of plastic containers which will significantly reduce their shelf life. Note how soft drinks begin to lose their carbonation in unopened plastic bottles after a certain period of time. Other important considerations are chilling characteristics, labeling, feel, aesthetics, and ease of opening.

10.106 Using specific examples, discuss the design issues involved in various products made of plastics versus reinforced plastics.

By the student. Reinforced plastics are superior to conventional plastics in terms of strength and strength- and stiffness-to-weight ratios, but not cost (see also Table 10.1 on p. 585. Consequently, their use is more common for critical applications. For example, the bucket supporting power-line service personnel is made of reinforced fiber, as are ladders and pressurized gas storage tanks (for oxygen, nitrogen, etc.) on the Space Shuttle.

10.107 Make a list of products, parts, or components that are not currently made of plastics, and offer reasons why they are not.

By the student. Consider, as examples, the following:

- Some products, such as machine guards or automobile fenders, give an impression of robustness if made of a metal but not if made of a plastic.

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- Plastics are generally not suitable for high temperature applications, such as automobile pistons, cookware, or turbine blades.
- Plastics are too compliant (flexible) for applications for machine elements such as ball bearings, cams, or highly-loaded gears.

10.108 In order to use a steel or aluminum container to hold an acidic material, such as tomato juice or sauce, the inside of the container is coated with a polymeric barrier. Describe the methods of producing such a container. (See also Chapter 7.)

By the student. The students are encouraged to section various cans and inspect their inner surfaces. The most common method is to (a) dissolve a thermosetting polymer in a chemical liquid carrier, usually a ketone, (b) spraying it onto the interior of the can, and (c) boiling off, leaving an adherent polymer coating. A less common approach is to laminate or coat the inside surface of the sheet stock with a metallic materials.

10.109 Using the information given in this chapter, develop special designs and shapes for possible new applications of composite materials.

By the student. This is a challenging topic and suitable for a technical paper. Consider, for example, the following two possibilities: (a) A tough transparent polymer, such as polycarbonate, that is reinforced with glass fibers. Strength will increase but transparency will be reduced. (b) A ceramic-matrix composite reinforced with copper, thus help diminish thermal cracking of the ceramic. If continuously dispersed throughout the matrix, the copper would conduct heat evenly throughout the matrix and thus reduce the thermal gradients in the composite. However, the composites operating temperature should be below the melting point of copper, even though ceramics resist high temperatures.

10.110 Would a composite material with a strong and stiff matrix and soft and flexible reinforcement have any practical uses? Explain.

By the student. This type of composite probably will have a higher toughness than the matrix alone, since the soft and flexible reinforcement material would blunt a propagating crack. However, such a composites usefulness will depend on whether or not it has a combination of higher strength and toughness than a composite with a ductile matrix and a strong reinforcement.

10.111 Make a list of products for which the use of composite materials could be advantageous because of their anisotropic properties.

By the student. Consider the following examples: cables, packaging tape, pressure vessels and tubing, tires (steel-belted radials), and sports equipment.

10.112 Name several product designs in which both specific strength and specific stiffness are important.

Specific strength and specific stiffness are important in applications where the material should be light and possess good strength and stiffness. A few specific applications are structural airplane components, helicopter blades, and automobile body panels.

10.113 Describe designs and applications in which strength in the thickness direction of a composite is important.

By the student. The thickness direction is important, for example, in thick-walled pressure vessels, with application for high-pressure service of hydraulic fluids as well as for residential water service. Radial reinforcement can be done with discontinuous fibers, provided they are oriented in the optimum direction. The students are encouraged to search the literature to provide various other examples.

10.114 Design and describe a test method to determine the mechanical properties of reinforced plastics in their thickness direction.

By the student. This is a challenging problem, and a literature search will be useful as a guide to developing appropriate techniques. The mechanical properties in the thickness direction are difficult to measure because of the small thickness as compared with the surface

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area of a specimen. Note, however, that tension tests in the thickness direction can be carried out by adhesively bonding both surfaces with metal plates, and then pulling the plates apart by some suitable means. A feasible and indirect approach may be to derive the properties in the thickness direction by performing tests in the other two principal directions, and then applying a failure criterion, as described in applied mechanics texts.

10.115 We have seen that reinforced plastics can be adversely affected by environmental factors, such as moisture, chemicals, and temperature variations. Design and describe test methods to determine the mechanical properties of composite materials under these conditions.

By the student. This is an important and challenging topic. Note that simple experiments, such as tension tests, are suitable when conducted in a controlled environment. Chambers are commonly installed around test specimens for such environmentally-controlled testing.

10.116 As with other materials, the mechanical properties of composites are obtained by preparing appropriate specimens and testing them. Explain what problems you might encounter in preparing specimens for testing and in the actual testing process itself.

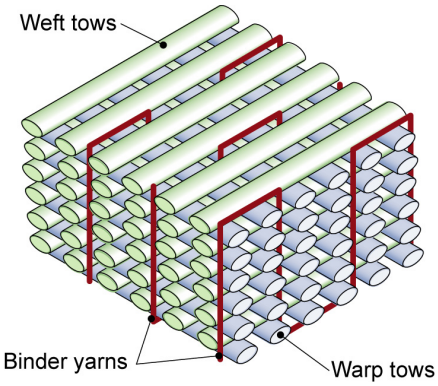
By the student. Testing composite materials can be challenging because of anisotropic behavior, with significant warping possible, as well as difficulties involved in preparing appropriate specimens and clamping them in the test equipment. Other approaches would measure deformation in more than one direction (as opposed to conventional tests where generally only the longitudinal strain is measured). Traditional dogbone specimens can be used.

10.117 Add a column to Table 10.1, describing the appearance of these plastics, including available colors and opaqueness.

By the student. Note that most thermoplastics can be made opaque, but only a few (such as acrylics and polycarbonates) are transparent. Most plastics are available in a variety of colors, such as polyethylene and ABS. Thermosets are opaque and come in very limited colors, such as black or brown.

10.118 It is possible to weave fibers in three dimensions, and to impregnate the weave with a curable resin. Describe the property differences that such materials would have compared to laminated composite materials.

By the student. This is a challenging topic, requiring literature search. An example of an orthogonal three-dimensional weave is shown in the accompanying figure, to give a perspective to the items listed below.



In general, the following comments can be made regarding three-dimensional weaves as compared to laminate composites:

- The through-thickness properties can be tailored for a particular application and can be superior for 3D-weaves.
- 3D woven composites have a higher delamination resistance and impact damage tolerance than 2D laminated composites.
- Different materials can be blended into a fiber prior to weaving. Indeed, most clothing involves blends of polymers or of polymers and natural fibers such as cotton or linen.
- The size of the weave can be varied more easily to allow for changes in the structure of such a material.
- 3D woven composites are more difficult and expensive to manufacture than 2D composites produced from laminated materials.
- 3D woven composites have lower mechanical properties than laminated composites.

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10.119 Conduct a survey of various sports equipment and identify the components that are made of composite materials. Explain the reason for and the advantages of using composites in these applications.

By the student. Consider, for example, the following:

- Tennis and racquetball racquets made of fiber reinforced composites. The main reasons are to reduce weight, improve the stiffness-to-weight ratio, and increase damping.
- Other examples with similar desired characteristics are softball bats, golf-club shafts, skis and ski bindings, and hockey and jai-alai sticks.

10.120 Instead of a having a constant cross section, it may be possible to make fibers or whiskers with a varying cross section or a fiber with a wavy surface. What advantages would such fibers have?

By the student. Perhaps the most compelling reason for this approach is associated with the relatively poor adhesive bond that may develop between fibers and the matrix in a composite material. In discontinuous-fiber-reinforced composites, especially, failure is associated with pull-out of the fiber (see Fig. 10.20). With a wavy fiber, there is mechanical interlocking between the matrix and fiber. Note, for example, steel bars for reinforced concrete with textured surfaces for better interfacial strength between the bar and the concrete.

10.121 Polymers (either plain or reinforced) can be a suitable material for dies in sheet-metal forming operations described in Chapter 7. Describe your thoughts, considering die geometry and any other factors that may be relevant.

By the student. See also p. 397. Recall that this is already a practice in operations such as rubber-pad forming and hydroforming (Section 7.5.3). The polymers must have sufficient rigidity, strength, and wear resistance. Considering these desirable characteristics, the use of plastic dies is likely to be appropriate and economical for relatively short production runs, and light forming forces. The main reason that polymer tooling has become of greater interest is the availability of rapid prototyping technologies that are capable of producing such tools and die inserts with low cost and lead times.

10.122 For ease of sorting for recycling, all plastic products are now identified with a triangular symbol with a single-digit number at its center and two or more letters under it. Explain what these numbers indicate and why they are used.

This information can be summarized as (see also top of p. 607):

1 Polyethylene
2 High-density polyethylene
3 Vinyl
4 Low-density polyethylene
5 Polypropylene
6 Polystyrene
7 Other

10.123 Obtain different kinds of toothpaste tubes, carefully cut them across with a sharp razor blade, and comment on your observations regarding the type of materials used and how the tube could be produced.

By the student. This is a topic suitable for some research. It will be noted that some collapsible tubes are blow molded, others are injection molded at one end and the other end is sealed by hot-tool welding (see Section 12.16.1). Another design is injection-molded rigid tubing where the toothpaste is pumped out during use. Note also that some collapsible tubes have walls that consist of multilayers of different materials and sealed on the closed end.

10.124 Design a machine that uses rapid-prototyping technologies to produce ice sculptures. Describe its basic features, commenting on the effect of size and shape complexity on your design.

By the student. Consider the following suggestions:

- A machine based on the principles of ballistic particle manufacturing (such as three-dimensional printing) to spray small

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droplets of water onto a frozen base, producing a sculpture incrementally, layer by layer.

- Sheets of ice can be produced and then cut with a heat source, such as a laser, to produce different shapes. The individual pieces would then be bonded, such as with a thin layer of water which then freezes, thus producing a sculpture.
- Layers of shaved ice can be sprayed, using a water jet, under controlled conditions (similar to three-dimensional printing).

Note that in all these processes, the outer surfaces of the sculpture will have to be smoothened for a better surface finish. This can be done, for instance, using a heat source (just as it is done in rounding the sharp edges of cut glass plates using a flame).

10.125 A manufacturing technique is being proposed that uses a variation of fused-deposition modeling, where there are two polymer filaments that are melted and mixed before being extruded to produce the workpiece. What advantages does this method have?

There are several advantages to this approach, including:

- If the polymers have different colors, blending the polymers can produce a part with a built-in color scheme.
- If the polymers have different mechanical properties, then functionally-graded materials can be produced, that is, materials with a designed blend of mechanical properties.
- Higher production rates and better workpiece properties may be achieved.
- If the second polymer can be leached, it can be developed into a technique for producing porous polymers or ship-in-the-bottle type parts.

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Chapter 11

Properties and Processing of Metal Powders, Ceramics, Glasses, Composites, and Superconductors

Questions

Powder metallurgy

11.1 Explain the advantages of blending different metal powders.

Metal powders are blended for the following basic reasons:

(a) Powders can be mixed to obtain special physical, mechanical, and chemical characteristics.

(b) Lubricants and binders can be mixed with metal powders.

(c) A uniform blend can impart better compaction properties and shorter sintering times.

11.2 Is green strength important in powder-metal processing? Explain.

Green strength is very important in powder-metal processing. When a P/M part has been ejected from the compaction die, it must have sufficient strength to prevent damage and fracture prior to sintering.

11.3 Give the reasons that injection molding of metal powders has become an important process.

Powder-injection molding has become an important process because of its versatility and economics. Complex shapes can be obtained at high production rates using powder metals that are blended with a polymer or wax. Also, the parts can be produced with high density to net or near-net shape.

11.4 Describe the events that occur during sintering.

In sintering, a green P/M part is heated to a temperature of 70-90% of the lowest melting point in the blend. At these temperatures, two mechanisms of diffusion dominate: direct diffusion along an existing interface, and, more importantly, vapor-phase material transfer to convergent geometries. The result is that the particles that were loosely bonded become integrated into a strong but porous media.

11.5 What is mechanical alloying, and what are its advantages over conventional alloying of metals?

In mechanical alloying, a desired blend of metal powders is placed into a ball mill (see Fig. 11.26b). The powders weld together when trapped between two or more impacting balls, and eventually are mechanically bonded and alloyed because of large plastic deformations

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they undergo. The main advantage of mechanical alloying is that the particles achieve a high hardness due to the large amount of cold work, and alloys which otherwise cannot be obtained through solidification can be achieved.

11.6 It is possible to infiltrate P/M parts with various resins, as well as with metals. What possible benefits would result from infiltration? Give some examples.

The main benefits to infiltration of a metal P/M part with another metal or polymer resin are:

(a) There can be a significant increase in strength;

(b) the infiltration can protect the P/M part from corrosion in certain environments;

(c) the polymer resin can act as a solid lubricant;

(d) the infiltrated part will have a higher density and mass in applications where this is desired.

11.7 What concerns would you have when electroplating P/M parts?

By the student. There are several concerns in electroplating (pp. 159-160) P/M parts, including:

(a) electroplating solutions are toxic and dangerous;

(b) it may be difficult to remove the residue liquid from inside P/M parts;

(c) it will be very difficult to perform plating in the interior of the part, as there is low current density. Thus, only the surface will be plated and it will be difficult to obtain a uniform surface finish.

11.8 Describe the effects of different shapes and sizes of metal powders in P/M processing, commenting on the magnitude of the shape factor of the particles.

The shape, size, size distribution, porosity, chemical purity, and bulk and surface characteristics of metal particles are all important. As expected, they have significant effects on permeability and flow characteristics during compaction in molds, and in subsequent sintering operations (Sections 11.2.20 and 11.3). It is beneficial to have angular shapes with approximately equally-sized particles to aid in bonding.

11.9 Comment on the shapes of the curves and their relative positions shown in Fig. 11.6.

At low compaction pressures, the density of P/M parts is low and at high compacting pressures, it approaches the theoretical density (that of the bulk material). Note that the concavity of the curves in Fig. 11.6a is downward, because in order to increase the density, smaller and smaller voids must be closed. Clearly, it is easier to shrink larger cavities in the material than smaller ones. Note that there is a minimum density at zero pressure. The results in Fig. 11.6b are to be expected because as density increases, there is less porosity and thus greater actual area in a cross-section; this leads to higher strength and electrical conductivity. The reason why elongation also increases with density is because of the lower number of porous sites that would reduce ductility (see Section 3.8.1).

11.10 Should green compacts be brought up to the sintering temperature slowly or rapidly? Explain.

Note that rapid heating can cause excessive thermal stresses in the part being sintered and can lead to distortion or cracking; on the other hand, it reduces cycle times and thus improve productivity. Slow heating has the advantage of allowing heating and diffusion to occur more uniformly.

11.11 Explain the effects of using fine vs. coarse powders in making P/M parts.

Coarse powders will have larger voids for the same compaction ratios, an analogy of which is the voids between marbles or tennis balls in a box (see also Fig. 3.2). The larger voids result in lower density, strength, stiffness, and thermal and electrical conductivity of P/M parts. The shape, size and distribution of particles, porosity, chemical purity, and bulk and surface characteristics are also important because they have significant effects on permeability and flow characteristics during compaction and in subsequent sintering operations.

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11.12 Are the requirements for punch and die materials in powder metallurgy different than those for forging and extrusion, described in Chapter 6? Explain.

In forging, extrusion, and P/M compaction, abrasive resistance is a major consideration in die and punch material selection. For that reason, the dies on these operations utilize similar and sometimes identical materials (see Table 3.6 on p. 114). Processes such as isostatic pressing utilize flexible molds, which generally is not used in forging and extrusion.

11.13 Describe the relative advantages and limitations of cold and hot isostatic pressing, respectively.

Cold isostatic pressing (CIP) and hot isostatic pressing (HIP) both have the advantages of producing compacts with effectively uniform density (Section 11.3.3). Shapes can be made with uniform strength and toughness. The main advantage of HIP is its ability to produce compacts with essentially 100% density, good metallurgical bonding, and good mechanical properties. However, the process is relatively expensive and is, therefore, used mainly for components in the aerospace industry or in making special parts.

11.14 Why do mechanical and physical properties depend on the density of P/M parts? Explain.

The mechanical properties depend on density for a number of reasons. Not only is there less material in a given volume for less dense P/M parts, hence lower strength, but voids are stress concentrations. Thus, the less dense material will have more and larger voids. The modulus of elasticity decreases with increasing voids because there is less material across a cross section and hence elongation is greater under the same load, as compared to a fully dense part. Physical properties such as electrical and thermal conductivity are also affected adversely because the less dense the P/M part is, the less material is available to conduct electricity or heat.

11.15 What type of press is required to compact powders by the set of punches shown in Fig. 11.7d? (See also Chapters 6 and 7.)

The operation shown in Fig. 11.7d would require a double-action press, so that independent movements of the two punches can be obtained. This is usually accomplished with a mechanical press.

11.16 Explain the difference between impregnation and infiltration. Give some applications for each.

The main difference between impregnation and infiltration is the media (see Section 11.5). In impregnation, the P/M part is immersed in a liquid, usually a lubricant, at elevated temperatures. The liquid is drawn into the P/M part by surface tension and fills the voids in the porous structure of the part. The lubricant also lowers the friction and prevents wear of the part in actual use. In infiltration, a lower-melting-point metal is drawn into the P/M part through capillary action. This is mainly done to prevent corrosion, although low-melting-point metals could be used for frictional considerations in demanding environments.

11.17 Explain the advantages of making tool steels by P/M techniques over traditional methods, such as casting and subsequent metalworking techniques.

From a cost standpoint, there may not be a major advantage because P/M itself requires special tooling to produce the part. However, some tool steels are very difficult to machine to desired shapes. Thus, by producing a P/M tooling, the machining difficulties are greatly reduced. P/M also allows the blending of components appropriate for cutting tools.

11.18 Why do compacting pressure and sintering temperature depend on the type of powder metal used? Explain.

Different materials require different sintering temperatures basically because they have different melting points. To develop good strength between particles, the material must be raised to a high enough temperature where diffusion and second-phase transport mechanisms can become active, which is typically around 90% of the material melting temperature on an absolute scale. As for the compacting pressure, it will depend on the type of metal powder such

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as its strength and ductility, the shape of the particles, and the interfacial frictional characteristics between the particles.

11.19 Name various methods of powder production and describe the morphology of powders produced.

By the student. Refer to Fig. 11.2. Briefly:

- Atomization: spherical (for gas atomized) or rounded (for water atomized).
- Reduction: spongy, porous, spherical or irregular
- Electrolytic deposition: dendritic
- Carbonyls: dense, spherical
- Comminution: irregular, flaky, angular
- Mechanical alloying: flaky, angular

11.20 Are there any hazards involved in P/M processing? If any, what are their causes?

There are several hazards in P/M processing; the major one is that powder metals can be explosive (particularly aluminum, magnesium, titanium, zirconium, and thorium). Thus, dust, sparks, and heat from friction should be avoided. In pressing, there are general concerns associated with closing dies, where a finger may be caught.

11.21 What is screening of metal powders? Why is it done?

In screening (Section 11.2.2), the metal powders are placed in a container with a number of screens; the top is coarsest, and the mesh is increasingly fine towards the bottom of the container. As the container is vibrated, the particles fall through the screens until their opening size is smaller than the particle diameter. Thus, screening separates the particles into ranges or sizes. This is done in order to have good control of particle size.

11.22 Why is there density variations in compacted metal powders? How is it reduced?

The main reason for density variation in compacting of powders is associated with mechanical locking and friction among the particles and the container walls. This leads to variations in pressure depending on distance from the punch and from the container walls (see Fig. 11.7). The variation can be reduced by using double-acting presses, lowering the frictional resistance of the punch and die surfaces, or by adding lubricants that reduce interparticle friction among the powders.

11.23 It has been stated that P/M can be competitive with processes such as casting and forging. Explain why this is so, commenting on technical and economic advantages.

By the student. Refer to Section 11.7. As an example, consider MIM which is commonly used with metals with high melting temperatures. This process requires fine metal powder that is mixed with a polymer and injection molded; the material costs are high. On the other hand, the applications for magnesium and aluminum die castings are in large volumes (camera frames, fittings, small toys) are economical and not as well-suited for MIM.

11.24 Selective laser sintering was described in Section 10.12.4 as a rapid prototyping technique. What similarities does this process have with the processes described in this chapter?

By the student. Recall that selective laser sintering uses the phenomena described in Section 11.4 and illustrated in Fig. 11.14. However, the high temperatures required to drive the material transfer is obtained from a laser and not by heating in a furnace as in P/M. Selective laser sintering also has significant part shrinkage.

11.25 Prepare an illustration similar to Fig. 6.28, showing the variety of P/M manufacturing options.

By the student.

Ceramics and other materials

11.26 Describe the major differences between ceramics, metals, thermoplastics, and thermosets.

By the student. This broad question will require extensive answers that can be tabulated by the student. Note, for example, that the chemistries are very different: ceramics are combinations of metals and non-metals, and plastics and thermosets involve repeating mers, usually based on long chains. Mechanically, the stress-strain behavior is very different as

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well; metals are linearly elastic and generally have high ductility and lower strain-hardening coefficients than thermoplastics. Ceramics are linearly elastic and brittle; thermoplastics flow above a critical temperature, while thermosets are elastic and brittle. Comparisons could also be made regarding various other mechanical, physical, and chemical properties, as well as their numerous applications.

11.27 Explain why ceramics are weaker in tension than in compression.

Ceramics are very sensitive to cracks, impurities, and porosity, and thus generally have low tensile strength and toughness (see, for example, Table 8.6 on p. 454). In compression, however, the flaws in the material do not cause the stress concentrations as they do in tension, hence compressive strength is high. (See also Section 3.8.)

11.28 Why do the mechanical and physical properties of ceramics decrease with increasing porosity? Explain.

Porosity can be considered microscopic air pockets in the ceramic. Thus, porosity will always decrease the strength of the ceramic because of the smaller cross-sectional area that has to support the external load. The holes in the material also act as stress concentrations to further lower the strength. The porosity also acts as crack initiation sites, thus decreasing toughness. Physical properties are affected likewise, in that pores in the ceramic are typically filled with air, which has much lower thermal and no electrical conductivity as compared with ceramics.

11.29 What engineering applications could benefit from the fact that, unlike metals, ceramics generally maintain their modulus of elasticity at elevated temperatures?

By the student. Consider, for example, that by retaining their high stiffness at elevated temperatures (see, for example, Fig. 11.24), dimensional accuracy of the parts or of the mechanical system can be maintained. Some examples are bearings, cutting tools, turbine blades, machine-tool components, and various high-temperature applications.

11.30 Explain why the mechanical-property data given in Table 11.7 have such a broad range. What is the significance of this wide range in engineering applications?

By the student. The mechanical properties given in Table 11.7 on p. 701 vary greatly because the properties of ceramics depend on the quality of the raw material, porosity, and the manner of producing the parts. Engineering applications that require high and reliable mechanical properties (e.g., aircraft and aerospace components) must assure that the materials and processing of the part are the best available.

11.31 List the factors that you would consider when replacing a metal component with a ceramic component. Give examples of such possible substitutions.

By the student. Review Section 11.8. Consider, for example, the following factors:

- The main drawbacks of ceramics are low tensile strength and toughness. Hence, the application of the metal component to be replaced should not require high tensile strength or impact resistance.
- If the ceramic part is subjected to wear, then the performance of the mating material is important. It could be that a three-body wear (see p. 147) would be introduced that could severely affect product life.
- Ceramics are typically probabilistic materials, that is, there is a wide range of mechanical properties in ceramic parts, whereas metals are typically deterministic and have a smaller distribution of strength. Thus, a major concern is whether or not a material is suitable for the particular design.
- As with all engineering applications, cost is a dominant consideration.

11.32 How are ceramics made tougher? Explain.

Ceramics may be made tougher by using high-purity materials, selecting appropriate processing techniques, embedding reinforcements,

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modifying surfaces and reducing surface defects, and by intentionally producing microcracks (less than 1 mm in size) in the ceramic to reduce the energy of propagation of an advancing crack tip. Another important technique is doping (see pp. 159 and 605), resulting in two or more phases, as in partially stabilized zirconia (PSZ) and transformation toughened zirconia (TTZ).

11.33 Describe situations and applications in which static fatigue can be important.

Static fatigue (see top of p. 702) occurs under a constant load and in environments where water vapor is present. Applications such as load-bearing members and sewer piping are susceptible to static fatigue if a tensile stress is developed in the pipe by bending or torsion. The student is encouraged to describe other applications.

11.34 Explain the difficulties involved in making large ceramic components. What recommendations would you make to overcome these difficulties?

By the student. Large components are difficult to make from ceramics, mainly because the ceramic must be fired to fuse the constituent particles. Firing leads to shrinkage of the part, resulting in significant warpage or residual stresses. With large parts, these factors become even greater, so that it is very difficult to produce reliable large ceramic parts. Such parts may be made by reinforcing the structure, or by producing the structure from components with a ceramic coating or from assembled ceramic components.

11.35 Explain why ceramics are effective cutting-tool materials. Would ceramics also be suitable as die materials for metal forming? Explain.

There are many reasons, based on the topics covered Chapters 6 through 8. Ceramics are very effective cutting materials, based especially on their hot hardness (see Table 8.6 on p. 454 and Figs. 8.30 and 8.37), chemical inertness, and wear resistance. In ceramic dies for forming, the main difficulties are that (1) ceramics are brittle, so any tensile or shear load would lead to crack propagation and failure, and (2) ceramics are generally difficult to machine or form to the desired die shapes with the required accuracy without additional finishing operations.

11.36 Describe applications in which the use of a ceramic material with a zero coefficient of thermal expansion would be desirable.

By the student. A ceramic material with a near-zero coefficient of thermal expansion (see Fig. 11.23 and Section 3.9.5) would have a much lower probability of thermal cracking when exposed to extreme temperature gradients, such as in starting an engine, contacting of two solid surfaces at widely different temperatures, and taking a frozen-food container and placing it in a hot oven. This property would thus be useful in applications where the ceramic is to be subjected to temperature ranges. Note also the properties of glass ceramics (Section 11.10.4).

11.37 Give reasons for the development of ceramic-matrix components. Name some present and other possible applications for such large components.

By the student. Ceramic-matrix components have been developed for high-temperature and corrosive applications where the strength-to-weight ratio of these materials is beneficial. The applications of interest include:

- aircraft engine components, such as combustors, turbines, compressors, and exhaust nozzles;
- ground-based and automotive gas turbine components, such as combustors, first and second stage turbine vanes and blades, and shrouds;
- engines for missiles and reusable space vehicles; and
- industrial applications, such as heat exchangers, hot gas filters, and radiant burners.

11.38 List the factors that are important in drying ceramic components, and explain why they are important.

Refer to Section 11.9.4. Since ceramic slurries may contain significant moisture content,

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resulting in 15-20% shrinkage, the removal of moisture is a critical concern. Recall that the moisture must be removed in order to fuse the ceramic particles. Important factors are: the rates at which moisture is removed (which can lead to cracking, if excessive), the initial moisture content (the higher it is, the greater the warpage and residual stress), and the particular material (as some materials will not warp as much as others and are more ductile and resistant to local defects).

11.39 It has been stated that the higher the coefficient of thermal expansion of glass and the lower its thermal conductivity, the higher is the level of residual stresses developed during processing. Explain why.

Refer to Sections 3.9.4 and 3.9.5. The coefficient of thermal expansion is important in the development of residual stresses because a given temperature gradient will result in a higher residual strain upon cooling. Thermal conductivity is important because the higher the thermal conductivity, the more uniform the temperature in the glass, and the more uniform the strains upon cooling. The more uniform the strains, the less the magnitude of residual stresses developed.

11.40 What types of finishing operations are typically performed on ceramics? Why are they done?

Ceramics are usually finished through abrasive methods, and they may also be glazed (see Section 11.9.5). Abrasive machining, such as grinding, is done to assure good tolerances and to remove surface flaws. Recall that tolerances may be rather poor because of shrinkage. Glazing is done to obtain a nonporous surface, which is important for food and beverage applications; it may also be done for decorative purposes.

11.41 What should be the property requirements for the metal balls used in a ball mill? Explain why these properties are important.

The metal balls in a ball mill (see Fig. 11.26b) must have very high hardness, strength, wear resistance, and toughness so that they do not deform or fracture during the milling operation. High stiffness and mass is desirable to maximize the compaction force (see p. 553).

11.42 Which properties of glasses allow them to be expanded and shaped into bottles by blowing? Explain.

The properties of glasses which allow them to be shaped into bottles by blowing is their viscoplasticity at elevated temperatures and their high strain-rate sensitivity exponent, m. Thus very large strains can be achieved as compared to metals. The strains can exceed even the superplastic aluminum and titanium alloys (see p. 44).

11.43 What properties should plastic sheet have when used in laminated glass? Explain.

A plastic sheet used in laminated glass (a) must obviously be transparent, (b) have a strong, intimate bond with the glass, and (c) have high toughness and strain to failure (see Fig. 10.13). The reason for the need for high strain to failure is to prevent shards of glass from being ejected, and thus prevent serious or fatal injuries during frontal impact.

11.44 Consider some ceramic products that you are familiar with and outline a sequence of processes performed to manufacture each of them.

By the student. As an example of a sequence of operations involved, consider the manufacture of a coffee cup:

- A ceramic slurry is mixed.
- The slurry is poured into the mold.
- The mold is allowed to rest, allowing the water in the slurry to be absorbed by the mold or to evaporate.
- The mold is opened and the green part is carefully removed.
- The handle can be a separate piece that is formed and attached at this stage; in some designs, the handle is cast integrally with the cup.
- The cup is then trimmed to remove the flash from the mold.
- It is then decorated and fired; it may be glazed and fired again.

11.45 Explain the difference between physical and chemical tempering of glass.

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By the student. Refer to Section 11.11.2. Note that in both physical and chemical tempering, compressive stresses are developed on the surface of the glass. In physical tempering, this is achieved through rapid cooling of the surface, which is then stressed in compression as the bulk cools. In chemical tempering, the same effect is achieved through displacement of smaller atoms at the glass surface with larger ones.

11.46 What do you think is the purpose of the operation shown in Fig. 11.27d?

In this operation, a bur-like tool (see p. 493) removes excess material from the top of the bottle and gives the desired shape to the neck.

11.47 Injection molding is a process that is used for plastics and powder metals as well as for ceramics. Why is it suitable for all these materials?

Injection molding can be used for any material (brought to a fluid state by heating) that will maintain its shape after forming and cooling. This is also the case with ceramic slurries and powder metals (in a polymer carrier, as in MIM.

11.48 Are there any similarities between the strengthening mechanisms for glass and those for other metallic and nonmetallic materials described throughout this text? Explain.

There are similarities. For example, metal parts as well as glass parts can be stress relieved or annealed to relieve surface residual stresses, which is in effect a strengthening mechanism. The results may be the same for both types of materials, even though the means of achieving them may differ. Note, for example, that compressive residual stresses are induced on glass surfaces through tempering, while metals are typically shot peened or surface rolled (see pp. 154-155).

11.49 Describe and explain the differences in the manner in which each of the following flat surfaces would fracture when struck with a large piece of rock: (a) ordinary window glass, (b) tempered glass, and (c) laminated glass.

By the student. Note that:

(a) When subjected to an impact load, ordinary window glass will shatter into numerous fragments or shards of various sizes.

(b) Tempered glass will shatter into small fragments.

(c) Laminated glass will shatter, but will not fly apart because the polymer laminate will hold the fragments in place and attached to the polymer.

11.50 Describe the similarities and the differences between the processes described in this chapter and in Chapters 5 through 10.

By the student. This could be a challenging task, as it requires a detailed knowledge of all the processes involved. Note, for example, that there are certain similarities between (a) forging and powder compaction, (b) slush casting and slip casting, (c) extrusion of metals and extruding polymers, and (d) drawing of metal wire and drawing of glass fibers. Students are encouraged to respond to this question with a broad perspective and giving several more examples.

11.51 What is the doctor-blade process? Why was it developed?

The doctor-blade process, shown in Fig. 11.28, produces thin sheets of ceramic. This process has, for example, been very cost-effective for applications such as making dielectrics in capacitors.

11.52 Describe the methods by which glass sheet is manufactured.

By the student. Glass sheet is produced by the methods described in Section 11.11 and in Fig. 11.32. Basically:

- In the drawing process (or the related rolling process), molten glass is pinched and pulled through rolls and then drawn down to the desired thickness.
- In the float method, a glass sheet floats on a bath of molten tin, producing a superior surface finish; the glass then cools in a lehr.

11.53 Describe the differences and similarities in producing metal and ceramic powders. Which of these processes would be suitable for producing glass powder?

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There are several methods of producing powders, but only a few are applicable to both ceramics and metals. The similarities include:

- Both can be produced by chemical reduction, mechanical milling, ball or hammer milling, and grinding.
- Both require screening to produce controlled distributions of particle sizes.
- Ball milling can be performed on either material to further reduce their particle size.

The differences include:

- Atomization is common for metals but not practical for ceramics, because of the high melting temperature of ceramics.
- The shape of the powders is different; metals are often atomized and hence spherical in shape, whereas ceramics are angular.
- Ceramics cannot be produced through electrolytic deposition.

Glass powders are of limited industrial interest (other than as glass lubrication in hot extrusion; see bottom of p. 318), but could conceivably be produced through hammer milling, grinding, or mechanical comminution.

11.54 How are glass fibers made? What application do these fibers have?

Glass fibers (see pp. 612-613) are bundle drawn using platinum dies. They are used as reinforcements in polymer composite materials, and as thermal and electrical insulation, and as a lubricant in hot extrusion.

11.55 Would you consider diamond a ceramic? Explain.

While diamond has many of the characteristics of ceramics, such as high hardness, brittleness, and chemical inertness, diamond is not a ceramic. By definition, a ceramic is a combination of a metal and a non-metal, whereas diamond is a form of carbon. (See Section 8.6.9.)

11.56 What are the similarities and differences between injection molding, metal injection molding, and ceramic injection molding?

By the student. The similarities between polymer injection molding and metal injection molding (MIM) and ceramic injection molding (CIM) include:

- The tool and die materials used are similar.
- Die design rules are similar.
- The pressures achieved and part sizes are the same, as is the equipment used.
- Operator skill required is comparable.

The differences include:

- Tool and die life for MIM or CIM is lower than that in polymer injection molding, because of the abrasiveness of the materials involved.
- Injection molding tooling requires heating (for reaction injection molding) or cooling (for injection molding) capabilities, whereas MIM and CIM do not require this capability.
- Cycle times for MIM and CIM are lower at the molding machine because cooling or curing cycles are not necessary.
- After molding, plastic parts have attained their full strength, whereas MIM and CIM parts require a sintering or firing step.

11.57 Aluminum oxide and partially stabilized zirconia are normally white in appearance. Can they be colored? If so, how would you accomplish this?

Coloring can be accomplished in a number of ways. First, an impurity can be mixes with the ceramic in order to change its color. Alternatively, a stain, paint, or dye can be applied after firing; some of the dyes may require a second firing step.

11.58 It was stated in the text that ceramics have a wider range of strengths in tension than do metals. List the reasons why this is so.

By the student. This question can be answered in a variety of ways. The students are encouraged to examine reasons for this characteristic, including the susceptibility of ceramics to flaws in tension and the range of porosity that ceramic parts commonly contain.

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Problems

11.59 Estimate the number of particles in a 500-g sample of iron powder, if the particle size is 50 μm.

From Table 3.3 on p. 106 and Fig. 11.6a, the density of iron is found to be $\rho = 7.86$ g/cm^3. The particle diameter, D, is 50 μm $= 0.005$ cm. The volume of each spherical powder is

$$V = \frac{4\pi}{3}\left(\frac{D}{2}\right)^3 = \frac{4\pi}{3}\left(\frac{0.005}{2}\right)^3$$

or $V = 6.545 \times 10^{-8}$ cm^3. Thus, its mass is

$$m = \rho V = (7.86)(6.545 \times 10^{-8}) = 5.14 \times 10^{-7} \text{ g}$$

Therefore, the number of particles in the sample is

$$N = \frac{500}{5.14 \times 10^{-7}} = 9.73 \times 10^8 = 973 \text{ million}$$

11.60 Assume that the surface of a copper particle is covered with a 0.1-μm-thick oxide layer. What is the volume occupied by this layer if the copper particle itself is 75 μm in diameter? What would be the role of this oxide layer in subsequent processing of the powders?

The volume of the oxide layer can be estimated as

$$V = 4\pi r^2 t = 4\pi(37.5\ \mu\text{m})^2(0.1\ \mu\text{m})$$

or $V = 1770\ \mu$m^3. Oxide layers adversely affect the bond strength between the particles during compaction and sintering, which, in turn, has an adverse effect on the strength and ductility of the P/M part. Its physical properties such as electrical and thermal conductivity are also affected.

11.61 Determine the shape factor for a flakelike particle with a ratio of surface area to thickness of $12 \times 12 \times 1$, for a cylinder with dimensional ratios 1:1:1, and for an ellipsoid with an axial ratio of $5 \times 2 \times 1$.

The volume of the flakelike particle is, in arbitrary units, $V = (12)(12)(1) = 144$. The equivalent diameter for a sphere is

$$V = \frac{\pi}{6}D^3$$

or, solving for D,

$$D = \sqrt[3]{\frac{6V}{\pi}} = \sqrt[3]{\frac{6(144)}{\pi}} = 6.50$$

The total surface area, A, of the particle is

$$A = (2)(12)(12) + (4)(12)(1) = 336.$$

Therefore,

$$\frac{A}{V} = \frac{336}{144} = 2.33$$

Thus, the shape factor is SF=(6.50)(2.33) = 15.17. For the ellipsoid particle, all cross sections across the three major and minor axes are elliptical in shape. (This is in contrast to an ellipsoid of revolution, where one cross section is circular.) The volume of an ellipsoid is

$$V = \frac{4}{3}\pi abc$$

where a, b, and c are the three semi-axes of the ellipsoid. Because of arbitrary units, we can calculate the volume of an ellipsoid with axes ratios of 5:2:1 as

$$V = \frac{4}{3}\pi abc = \frac{4}{3}(5)(2)(1) = 41.89$$

The equivalent diameter for a sphere is

$$D = \sqrt[3]{\frac{6V}{\pi}} = \sqrt[3]{\frac{6(41.89)}{\pi}} = 4.3$$

It can be shown that the surface area of the ellipsoid is given by the expression

$$A = \left(\frac{\pi^2}{2}\right)(a+b)(c)$$

where c is the semi-axis of the longest dimension of the ellipse. Thus, again using arbitrary units,

$$A = \left(\frac{\pi^2}{2}\right)(2+1)(5) = 74.02$$

Therefore,

$$\frac{A}{V} = \frac{74.02}{41.89} = 1.77$$

Hence, the shape factor is SF= (4.30)(1.77) = 7.61.

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11.62 It was stated in Section 3.3 that the energy in brittle fracture is dissipated as surface energy. We also noted that the comminution process for powder preparation generally involves brittle fracture. What are the relative energies involved in making spherical powders of diameters 1, 10, and 100 μm, respectively?

First, note that the surface energy is proportional to the surface area generated during comminution. The surface area of a spherical particle is $4\pi r^2 = \pi D^2$. Consequently, the relative energies will be proportional to the diameter squared, or 1, 100, and 10,000, respectively.

11.63 Referring to Fig. 11.6a, what should be the volume of loose, fine iron powder in order to make a solid cylindrical compact 25 mm in diameter and 15 mm high?

The volume of the cylindrical compact is $V = \pi[(25)^2/4]15 = 7360$ mm^3. Loose, fine iron powder has a density of about 1.40 g/cm^3 (see Fig. 11.6a). Density of iron is 7.86 g/cm^3 (see Table 3.1). Therefore, the weight of iron needed is

$$\begin{aligned} W &= \rho V \\ &= (7.86 \text{ g/cm}^3)(7360 \text{ mm}^3)(10^{-3}\frac{\text{cm}^3}{\text{mm}^3}) \end{aligned}$$

or $W = 57.8$ g. Thus, the initial volume is

$$V = \frac{W}{\rho} = \frac{57.8}{1.40} = 41.3 \text{ cm}^3$$

11.64 In Fig. 11.7e, we note that the pressure is not uniform across the diameter of the compact. Explain the reasons for this variation.

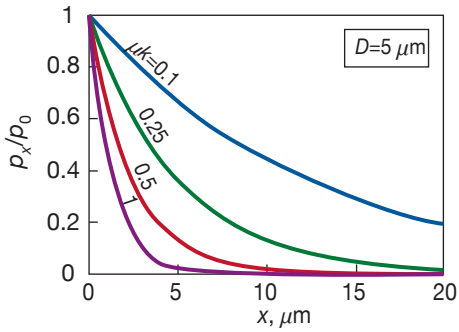
Note in the figure that the pressure drops towards the center of the compact; this is because of the internal frictional resistance in the radial direction. This situation is similar to forging with friction, as described in Section 6.2.2. Also note that the pressure drop is steepest at the upper (punch) surface, and that at the level where the pressure is in the range of 200-300 MPa, the pressure is rather uniform across the cross section of the compact.

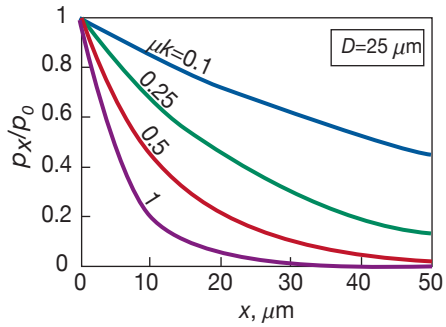
11.65 Plot the family of pressure-ratio p_x/p_o curves as a function of x for the following ranges of process parameters: $\mu = 0$ to 1, $k = 0$ to 1, and $D = 5$ mm to 50 mm.

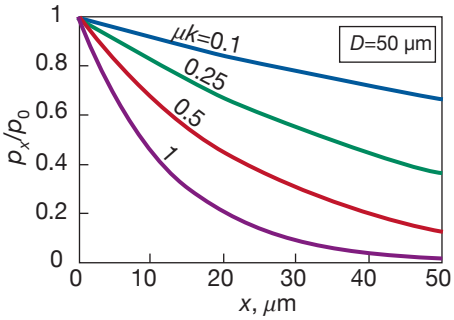
The key equation is Eq. (11.2) on p. 680:

$$p_x = p_o e^{-4kx/D}$$

The results are plotted in three graphs, for $D = 5$ μm, $D = 25$ μm, and $D = 50$ μm.







11.66 Derive an expression, similar to Eq. (11.2), for compaction in a square die with dimensions a by a.

Referring to Fig. 11.8 and taking an element with a square cross section, the following equation represents equilibrium:

$$a^2 p_x - a^2(p_x + dp_x) - 4a(\mu\sigma_x)\,dx = 0$$

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which reduces to

$$a dp_x + 4\mu\sigma_x\, dx = 0$$

This equation is the same as that in Section 11.3.1. Therefore, the expression for the pressure at any x is

$$p_x = p_o e^{-4\mu k x/a}$$

11.67 For the ceramic described in Example 11.7, calculate (a) the porosity of the dried part if the porosity of the fired part is to be 9%, and (b) the initial length, L_o, of the part if the linear shrinkages during drying and firing are 8% and 7%, respectively.

(a) For this case we have

$$V_a = (1 - 0.09)V_f = 0.91V_f$$

Because the linear shrinkage during firing is 7%, we can write

$$V_d = V_f/(1 - 0.07)^3 = 1.24V_f$$

Therefore,

$$\frac{V_a}{V_d} = \frac{0.91}{1.24} = 0.73, \text{ or } 73\%$$

Consequently, the porosity of the dried part is (1 - 0.73) = 0.27, or 27%.

(b) We can now write

$$\frac{(L_d - L)}{L_d} = 0.07$$

or

$$L = (1 - 0.07)L_d$$

Since $L = 20$ mm,

$$L_d = 20/0.93 = 21.51 \text{ mm}$$

and thus

$$L_o = (1 + 0.08)L_d = (1.08)(21.51)$$

or $L_o = 23.23$ mm.

11.68 What would be the answers to Problem 11.67 if the quantities given were halved?

(a) For this case, we have

$$V_a = (1 - 0.045)V_f = 0.955V_f$$

Because the linear shrinkage during firing is 3.5%, we write

$$V_d = V_f/(1 - 0.035)^3 = 1.112V_f$$

Therefore,

$$V_a/V_d = 0.955/1.112 = 0.86, or 86\%$$

Consequently, the porosity of the dried part is (1 - 0.86) = 0.14, or 14%.

(b) We can now write

$$\frac{(L_d - L)}{L_d} = 0.035$$

or

$$L = (1 - 0.035)L_d$$

Since $L = 20$ mm, we have

$$L_d = \frac{20}{0.965} = 20.73 \text{ mm}$$

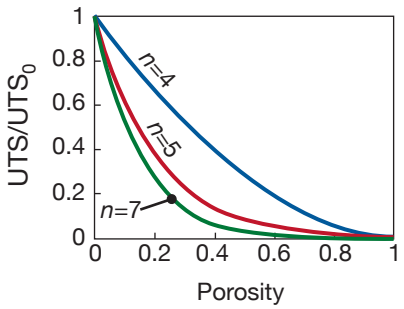
and thus

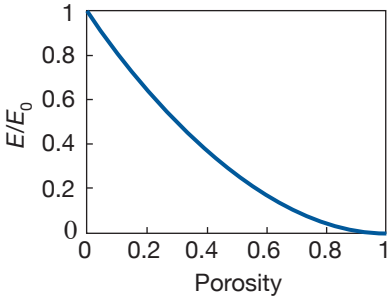
$$L_o = (1 + 0.04)L_d = (1.04)(20.73)$$

or $L_o = 21.56$ mm.

11.69 Plot the UTS, E, and k values for ceramics as a function of porosity, P, and describe and explain the trends that you observe in their behavior.

The plots are given below.





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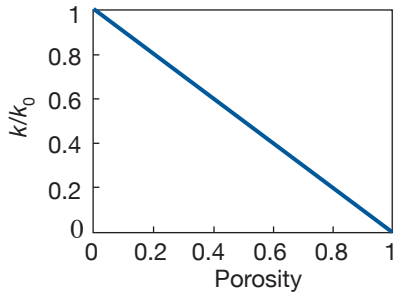


11.70 Plot the total surface area of a 1-g sample of aluminum powder as a function of the natural log of particle size.

The density of aluminum is 2.7 g/cm^3. The mass of each particle is:

$$m = \rho V = \left(2.7 \text{ g/cm}^3\right)\left(\frac{4}{3}\pi\right)\left(\frac{D}{2}\right)^3$$

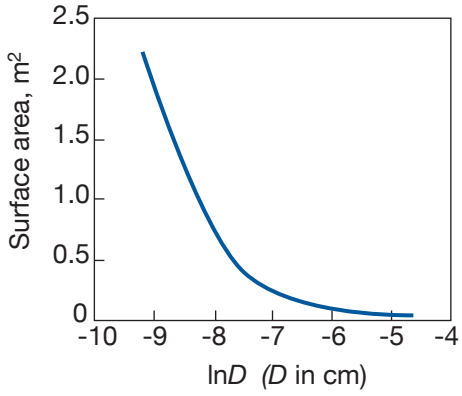
hence the number of particles is given by

$$N = \frac{1 \text{ g}}{m} = \frac{1}{(2.7)\left(\frac{\pi}{6}D^3\right)} = \left(0.707 \text{ cm}^3\right)\left(D^{-3}\right)$$

The total surface area of these particles is

$$A = N\pi D^2 = (0.707 \text{ cm}^3)(D^{-3})\pi D^2$$

or $A = (2.22 \text{ cm}^3)D^{-1}$, where D is in cm (μm $\times$ 10,000). The plot is shown below.



11.71 Conduct a literature search and determine the largest size of metal powders that can be produced in atomization chambers.

By the student. The answer will depend on the material and desired particle morphology. Spherical particles will be in the sub-mm sizes (tens to hundreds of microns), while other shapes can approach a few mm in average diameter.

11.72 A coarse copper powder is compacted in a mechanical press at a pressure of 20 tons/in^2. During sintering, the green part shrinks an additional 8%. What is the final density of the part?

From Fig. 11.6, the copper density after compaction is around 7 g/cm^3. Since the material shrinks an additional 8% during sintering, the volume is $1/(0.92)^3$ times the original volume. Thus, the density will be around 8.99 g/cm^3.

11.73 A gear is to be manufactured from iron powder. It is desired that it have a final density that is 90% of that of cast iron, and it is known that the shrinkage in sintering will be approximately 5%. For a gear 2.5-in. in diameter and with a 0.75-in. hub, what is the required press force?

From Table 3.3 on p. 106, the density of iron is 7.86 g/cm^3. For the final part to have a final density of 90% of this value, the density after sintering must be 7.07 g/cm^3. Since the part contracts 5% during sintering, the density before sintering must be 6.06 g/cm^3. Referring to Fig. 11.6a, the required pressure for this density is around 20 tons/in^2. The projected area is $A = \pi/4(2.5^2 - 0.75^2) = 4.47$ in^2. The required force is then 89 tons, or approximately 90 tons.

11.74 What volume of powder is needed to make the gear in Problem 11.73 if its thickness is 0.5 in?

Refer to the solution to Problem 11.73. The volume of the gear is the product of the projected area and its thickness. The actual surface area of the gear is not given, but we can estimate the amount of powder needed by assuming that the diameter given is the pitch diameter and that the part can be treated as a cylinder with a circular cross section with a 2.5 in. diameter and a 0.75-in. hole. The projected area, as calculated in Problem 11.73, is $A = 4.47$ in^2. Thus, the volume is

$$V = Ah = (4.47)(0.5) = 2.235 \text{ in}^3 = 36.6 \text{ cm}^3$$

Therefore, the weight of the gear is (7.07 g/cm^3)(36.6 cm^3)=260 g. From Fig. 11.6a, loose fine iron powder has a density of around

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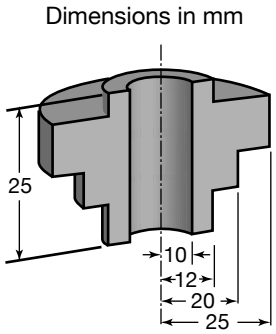
1.4 g/cm^3. Therefore, the volume of powder required is

$$V = \frac{m}{\rho} = \frac{260 \text{ g}}{1.4 \text{ g/cm}^3} = 185 \text{ cm}^3$$

11.75 The axisymmetric part shown in the accompanying figure is to be produced from fine copper powder and is to have a tensile strength of 200 MPa. Determine the compacting pressure and the initial volume of powder needed.



From Fig. 11.6b, the density of the copper part must be around 8.5 g/cm^3 to achieve the strength of 200 MPa. From Fig. 11.6a, the required pressure is around 1000 MPa. The press force will be determined by the largest cross-sectional area, which has the 25 mm outer diameter. The cross-sectional area is

$$\begin{aligned} A &= \frac{\pi}{4}\left(D_o^2 - D_i^2\right) \\ &= \frac{\pi}{4}\left(0.025^2 - 0.010^2\right) \end{aligned}$$

or $A = 4.123 \times 10^{-4}$ m^2. Therefore, the required force is

$$F = pA = (1000 \text{ MPa})(4.123 \times 10^{-4} \text{ m}^2)$$

or $F = 412$ kN. From the given geometry, the final part volume is found to be 8.0 cm^3, and hence the mass required is

$$m = \rho V = (8.5 \text{ g/cm}^3)(8.0 \text{ cm}^3) = 68 \text{ g}$$

From Fig. 11.6a, the apparent density of fine copper powder is 1.44 g/cm^3, so that the required powder volume is

$$V = \frac{m}{\rho} = \frac{68 \text{ g}}{1.44 \text{ g/cm}^3} = 45 \text{ cm}^3$$

11.76 What techniques, other than the powder-in-tube process, could be used to produce superconducting monofilaments?

Other principal superconductor-shaping processes are:

(a) coating of silver wire with superconducting material,

(b) deposition of superconductor films by laser ablation,

(c) doctor-blade process (see Section 11.9.1),

(d) explosive cladding (see Section 12.11), and

(e) chemical spraying.

11.77 Describe other methods of manufacturing the parts shown in Fig. 11.1a. Comment on the advantages and limitations of these methods over P/M.

By the student. Several alternative methods for manufacturing the parts can be discussed. For example, the parts could be machined, in which case the machined part may have better dimensional accuracy and surface finish, and would be less expensive for short production runs. The P/M part would be less expensive for large production runs and would likely be less dense. As another example, consider forging of these parts; the forging would be denser and stronger, and have similar surface finish if cold forged. However, a P/M part would likely have a lower density and would be produced without flash.

11.78 If a fully-dense ceramic has the properties of UTS$_o$ = 180 MPa and E_o = 300 GPa, what are these properties at 20% porosity for values of n = 4, 5, 6, and 7, respectively?

Inserting the appropriate quantities into Eqs. (11.5) and (11.6) on p. 701, we obtain the following:

n	UTS (MPa)	E (GPa)
4	80.9	196.8
5	66.2	196.8
6	54.2	196.8
7	44.4	196.8

Note that the magnitude of n does not affect the magnitude of E.

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11.79 Calculate the thermal conductivities for ceramics at porosities of 1%, 5%, 10%, 20%, and 30% for $k_o = 0.7$ W/m-K.

Equation (11.7) is needed to solve this problem, which gives the thermal conductivity as a function of porosity as

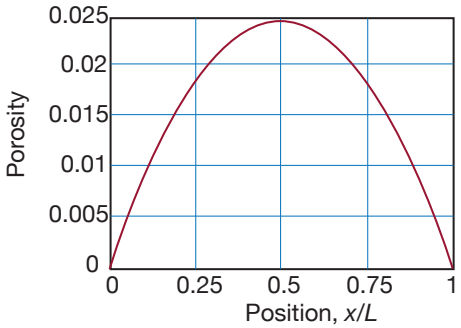
$$k = k_o(1 - P)$$

Inserting the values into the equation, we obtain thermal conductivities of:

$P = 1\%$	$k = 0.693$ W/mK
5	0.665
10	0.630
20	0.56
30	0.49

11.80 A ceramic has $k_o = 0.65$ W/m-K. If this ceramic is shaped into a cylinder with a porosity distribution of $P = 0.1(x/L)(1 - x/L)$, where x is the distance from one end of the cylinder and L is the total cylinder length, estimate the average thermal conductivity of the cylinder.

The plot of porosity is given below:



For the remainder of the problem, use $X = x/L$. The average porosity is then given by

$$\begin{aligned} \bar{P} &= \int_0^1 0.1X(1 - X)dX \\ &= \int_0^1 \left(-0.1X^2 + 0.1X\right) dX \\ &= 0.0167 \end{aligned}$$

Since the thermal conductivity is linearly related to the porosity, the average porosity can be used, so that the average thermal conductivity is:

$$\bar{k} = k_o\left(1 - \bar{P}\right) = (0.65)(1 - 0.0167)$$

or $\bar{k} = 0.639$ W/mK.

11.81 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

Design

11.82 Make sketches of several P/M products in which density variations would be desirable. Explain why, in terms of the function of these parts.

By the student. Any kind of minimum-weight design application would be appropriate, such as aerospace and automotive, where lightly loaded regions can be reduced in weight by making them more porous. With bearing surfaces, a greater density at the surface is desirable, while a substrate need not be as dense.

11.83 Compare the design considerations for P/M products with those for products made by (a) casting and (b) forging. Describe your observations.

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By the student. Note that design considerations for P/M parts (Section 11.6) are similar to those for casting (Section 5.12) and forging (Section 6.2.7). The similarities are due to the necessity of removing the parts from the molds or dies. Hence, tapers should be used whenever possible and internal cavities are difficult to produce. Large flat surfaces should be avoided, and the section thickness should be uniform as much as possible. There are many similarities with casting and forging part design, mainly because P/M parts need to be ejected, just as in forging, and the pattern for casting need to be removed. There are some differences. For example, engraved or embossed lettering is difficult in P/M but can be done easily in casting. P/M parts should be easy to eject; casting designs are more flexible in this regard.

11.84 It is known that in the design of P/M gears, the distance between the outside diameter of the hub and the gear root should be as large as possible. Explain the reasons for this design consideration.

The reason for this is twofold. First, it is very difficult to develop a sufficiently high pressure in the cross section containing the root if the distance is small. Secondly, if the distance is small, it acts as a high stress concentration, which could cause part failure prior to being sintered, especially during ejection.

11.85 How are the design considerations for ceramics different, if any, than those for the other materials described in this chapter?

By the student. Refer to Section 11.12. Consider, for example, the fact that ceramics are very notch sensitive, hence brittle, and are not suitable for impact or energy-dissipating type loading, and also not usable where any deformation is foreseeable. On the other hand, ceramics have exceptional properties at high temperatures, are very strong in compression, and are resistant to wear because of their high hardness and inertness to most materials.

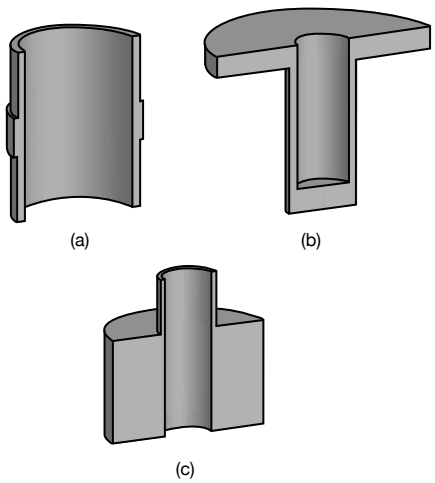
11.86 Are there any shapes or design features that are not suitable for production by powder metallurgy? By ceramics processing? Explain.

By the student. Neither ceramics nor P/M parts are suitable for large parts (see, for example, Fig. 11.10). For example, bolts, architectural channels, and some biomedical implants are poor P/M applications. Also, fatigue applications are generally not appropriate for P/M parts because cracks can propagate easier through the structure. The students are encouraged to comment further.

11.87 What design modifications would you recommend for the part shown in Problem 11.75?

By the student. A number of design changes would be advisable to increase manufacturability using P/M techniques. For example, it is advisable that the steps have a taper to aid in ejection (see Fig. 11.17). The sharp radii should be larger. The part is unbalanced, and the flange, though probably acceptable, could be made smaller, if appropriate.

11.88 The axisymmetric parts shown in the accompanying figure are to be produced through P/M. Describe the design changes that you would recommend.



There are several design changes that could be advisable, and the students are encouraged to develop lists of their own recommendations. Some considerations are:

(a) Part (a):

- The part has very thin walls, and it would be advisable to have less severe aspect ratios.

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- The part cannot be pressed in its current shape, but could conceivably be metal injection molded.
- Sharp corners are not advisable; radii should be incorporated for metal injection molding, and chamfers for pressed parts.

(b) Part (b): Same as in (a)

(c) Part (c): Same as in (a), and the flanges should comply with the recommendations given in Fig. 11.19.

11.89 Assume that in a particular design, a metal beam is to be replaced with a beam made of ceramics. Discuss the differences in the behavior of the two beams, such as with respect to strength, stiffness, deflection, and resistance to temperature and to the environment.

By the student. This is an open-ended problem that can be answered in a number of ways by the students. They can, for example, consider a cantilever, where the deflection at the end of the cantilever is,

$$y = -\frac{Pl^3}{3EI}$$

and then compare materials that would give the same deflection for different beam heights, widths, or volumes. One could also consider the lightest weight cantilever that could support the load or one that would have a small deflection under the load. Students are encouraged to examine this problem in depth.

11.90 Describe your thoughts regarding designs of internal combustion engines using ceramic pistons.

By the student. There are several difficulties associated with such designs. For example, lubricants (see Section 4.4.4) typically are formulated for use with aluminum and steel parts, and the boundary additives may not be effective on a ceramic surface, so higher wear rates may occur. Ceramic wear particles will be much harder than metal engine blocks or cylinder liners, and will raise concerns of three-body wear (see p. 147). The entire engine needs to be redesigned to account for the reduced mass in the pistons and other components. This can be beneficial since higher speeds can be attained, but the engine may run rougher at low speeds. (See the discussion of *coefficient of fluctuation* in Hamrock, Jacobson, and Schmid, *Fundamentals of Machine Elements*, 2d ed., p. 464.)

11.91 Assume that you are employed in technical sales. What applications currently using non-P/M parts would you attempt to develop? What would you advise your potential customers during your sales visits? What kind of questions do you think they would ask?

By the student. This is a challenging question that requires knowledge of parts that are and are not currently produced by P/M. It would be advisable for the instructor to limit the discussion to a class of product, such as P/M gears. In this case, the questions that would be asked of customers include:

(a) Are you aware of the advantages of P/M processes?

(b) Are you aware of the tribological advantages of P/M parts?

(c) Are you interested in unique alloys or blends that can only be achieved with P/M technologies?

(d) Is it beneficial to achieve a 5-10% weight savings using porous P/M parts?

Typical anticipated questions from the customer could include:

(a) Is there a cost or performance advantage? Are there any disadvantages?

(b) We have had no failures, so why should we change anything?

(c) Are the P/M materials compatible.

11.92 Pyrex cookware displays a unique phenomenon: it functions well for a large number of cycles and then shatters into many pieces. Investigate this phenomenon, list the probable causes, and discuss the manufacturing considerations that may alleviate or contribute to such failures.

By the student. This is a challenging question. The basic phenomenon appears to be that, with each thermal stress cycle new flaws in the material may develop, and existing flaws begin to grow. When the flaws have reached a critical

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size (see p. 102), the part fails under normal use. Note that any manufacturing that result in a larger initial flaw, or being subjected to less effective tempering, will contribute to the problem.

11.93 It has been noted that the strength of brittle materials, such as ceramics and glasses, are very sensitive to surface defects such as scratches (notch sensitivity). Obtain some pieces of these materials, make scratches on them, and test them by carefully clamping in a vise and bending them. Comment on your observations.

By the student. This experiment can be performed using a glass cutter to make a deep and sharp scratch on the glass. It can be demonstrated that glass with such a scratch can be easily broken with bare hands. Note also the direction of the bending moment with respect to the direction of the scratch. As a comparison, even a highly heat-treated aluminum plate (i.e., brittle behavior) will not be nearly as weakened when a similar scratch is made on its surface. Note that special care must be taken in performing these experiments, using work gloves and eye protection and the like.

11.94 Make a survey of the technical literature and describe the differences, if any, between the quality of glass fibers made for use in reinforced plastics and those made for use in fiber-optic communications. Comment on your observations.

By the student. The glass fibers in reinforced plastics has a much smaller diameter and has to be of high quality for high strength. The glass fibers for communications applications are formulated for optical properties and the strength is not a major concern, although some strength is needed for installation.

11.95 Describe your thoughts on the processes that can be used to make (a) small ceramic statues, (b) white ware for bathrooms, (c) common brick, and (d) floor tile.

By the student. The answers will vary because of the different manufacturing methods used for these products. Some examples are:

(a) Small ceramic statues are usually made by slip casting, then fired to fuse the particles and develop strength, followed by decorating and glazing.

(b) White ware for bathrooms are either slip cast or pressed, then fired, and sometimes glazed and re-fired.

(c) Common brick is wet pressed or slip cast, then fired.

(d) Floor tile is hot pressed or dry pressed, fired, and sometimes glazed and re-fired.

11.96 As described in this chapter, one method of producing superconducting wire and strip is by compacting powders of these materials, placing them into a tube, and drawing them through dies, or rolling them. Describe your thoughts concerning the possible difficulties involved in each step of this production.

By the student. Concerns include fracture of the green part before or during drawing, and its implications; inhomogeneous deformation that can occur during drawing and rolling and its possible effects as a fracture-causing process; the inability of the particles to develop sufficient strength during this operation; and possible distortion of the part from its drawn or rolled shape during sintering.

11.97 Review Fig. 11.18 and prepare a similar figure for constant-thickness parts, as opposed to the axisymmetric parts shown.

By the student. The figure will be very similar to Fig. 11.18, as the design rules are not necessarily based on the axisymmetric nature of the parts.

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Chapter 12

Joining and Fastening Processes

Questions

12.1 Explain the reasons that so many different welding processes have been developed.

A wide variety of welding processes have been developed for several reasons. There are many types of metals and alloys with a wide range of mechanical, physical, and metallurgical properties and characteristics. Also, there are numerous applications involving a wide variety of component shapes and thicknesses. For example, small or thin parts that cannot be arc welded can be resistance welded, and for aerospace applications, where strength-to-weight ratio is a major consideration, laser-beam welding and diffusion bonding are attractive processes. Furthermore, the workpiece may not be suitable for in-plant welding, and the welding process may have to be brought to the site, such as pipelines and large structures. (See also Section 12.1.)

12.2 List the advantages and disadvantages of mechanical fastening as compared with adhesive bonding.

By the student. Advantages of mechanical fastening over adhesive bonding:

(a) disassembly is easier (bolted connections);
(b) stronger in tension;
(c) preloading is possible; and
(d) no need for large areas of contact.

Limitations:

(a) often costlier;
(b) requires assembly;
(c) weaker in shear; and
(d) more likely to loosen (bolted connections).

12.3 What are the similarities and differences between consumable and nonconsumable electrodes?

By the student. Review Sections 12.3 and 12.4. Comment, for example, on factors such as the role of the electrodes, the circuitry involved, the electrode materials, and the manner in which they are used.

12.4 What determines whether a certain welding process can be used for workpieces in horizontal, vertical, or upside-down positions, or for all types of positions? Explain, giving appropriate examples.

By the student. Note, for example, that some welding operations (see Table 12.2 on p. 734) cannot take place under any conditions except horizontal, such as submerged arc welding, where a granular flux must be placed on the workpiece. If a process requires a shielding gas, it can be used in vertical or upside-down positions. Oxyacetylene welding would be difficult upside-down because the flux may drip away from the surface instead of penetrating the joint.

12.5 Comment on your observations regarding Fig. 12.5.

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By the student. The students are encouraged to develop their answers considering the significance of the layered weld beads and the quality of their interfaces. For example, there may be concerns regarding the weld strength since the interfaces between adjacent beads may have some slag or surface contaminants that have not been removed. The heat-affected zone and fatigue implications of such welds are also a significant concern.

12.6 Discuss the need for and role of fixtures in holding workpieces in the welding operations described in this chapter.

By the student. The reasons for using fixtures are basically to assure proper alignment of the components to be joined, reduce warpage, and help develop good joint strength. The fixtures can also be a part of the electrical circuit in arc welding, where a high clamping force reduces the contact resistance. See also Section 14.11.1.

12.7 Describe the factors that influence the size of the two weld beads in Fig. 12.13.

The reason why electron-beam weld beads are narrower than those obtained by arc welding is that the energy source in the former is much more intense, confined, and controllable, allowing the heating and the weld bead to be more localized. Other factors that influence the size of the weld bead are workpiece thickness, material properties, such as melting point and thermal conductivity. See also pp. 749-751.

12.8 Why is the quality of welds produced by submerged arc welding very good?

Submerged arc welding (see Fig. 12.6) has very good quality because oxygen in the atmosphere cannot penetrate the weld zone where the shielding flux protects the weld metal. Also, there are no sparks, spatter, or fumes as in shielded metal arc and some other welding process.

12.9 Explain the factors involved in electrode selection in arc welding processes.

By the student. Refer to Section 12.3.8. Electrode selection is guided by many factors, including the process used and the metals to be welded.

12.10 Explain why the electroslag welding process is suitable for thick plates and heavy structural sections.

Electroslag welding (see Fig. 12.8) can be performed with large plates because the temperatures attainable through electric arcs are very high. A continuous and stable arc can be achieved and held long enough to melt thick plates.

12.11 What are the similarities and differences between consumable and nonconsumable electrode arc welding processes?

By the student. Similarities: both require an electric power source, arcing for heating, and an electrically-conductive workpiece. Differences: the electrode is the source of the weld metal in consumable-arc welding, whereas a weld metal must be provided in nonconsumable-arc welding processes.

12.12 In Table 12.2, there is a column on the distortion of welded components, ranging from lowest to highest. Explain why the degree of distortion varies among different welding processes.

By the student. Refer to Table 12.2 on p. 734. The distortion of parts is mainly due to thermal warping because of temperature gradients developed within the component. Note that the lowest distortions are in electron beam and laser beam processes, where the heat is highly concentrated in narrow regions and with deeper penetration. This is unlike most other processes where the weld zones are large and distortion can be extensive.

12.13 Explain why the grains in Fig. 12.16 grow in the particular directions shown.

The grains grow in the directions shown in Fig. 12.16 because of the same reasons grains grow away from the wall in casting process solidification, described in Section 5.2. Heat flux is in the opposite direction as grain growth, meaning a temperature gradient exists in that direction, so only grains oriented in the direction perpendicular from the solid-metal substrate will grow.

12.14 Prepare a table listing the processes described in this chapter and providing, for each process,

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the range of welding speeds as a function of workpiece material and thickness.

By the student. This is a good assignment for students, although it can be rather demanding because such extensive data is rarely available, except with a wide range or only for a particular group of materials. Consequently, it can be difficult to compare the processes; they nevertheless should be encouraged to develop such a list as best they can.

12.15 Explain what is meant by *solid state welding*.

As descried briefly on p. 733, in solid state welding, the metals to be joined do not melt; there is no liquid state in the interface. Note that there are six processes listed under this category.

12.16 Describe your observations concerning Figs. 12.19 through 12.21.

By the student. This is a challenging question and students are encouraged to develop and list as many answers as they can. For example, they can consider the crack locations, develop an ability to identify them through inspection, describe the causes of the defects, and the effects of different workpiece materials and processing conditions.

12.17 What advantages does friction welding have over the other joining methods described in this chapter?

By the student. As described in Section 12.9, the main advantages of friction welding are that the entire cross-sectional area can be welded, instead of a mere bead along the periphery, and is suitable for a wide variety of materials. Also, with proper process control, the weld zone can be very small and thin, so that thermal distortions will be minimal.

12.18 Why is diffusion bonding, when combined with superplastic forming of sheet metals, an attractive fabrication process? Does it have any limitations?

By the student. As shown in Fig. 12.41, diffusion bonding combined with superplastic forming can produce lightweight, rigid, and strong aerospace structures with high stiffness-to-weight ratios. The main drawback is the long production time and the high costs involved, which may be justified for many aerospace applications. The students are encouraged to find other examples of applications for this important process.

12.19 Can roll bonding be applied to various part configurations? Explain.

Roll bonding (Fig. 12.28) is mainly used in flat rolling, although other applications may be possible. The important consideration is that the pressure (normal stress) between the sheets to be joined be sufficiently high and the interfaces are clean and free of oxide layers. To meet this condition for shapes other than flat is likely to be a difficult task and involve complex tooling. Also, any significant variation in pressure during rolling can make the bonded structure become not uniform and unreliable. The student is encouraged to search the literature and attempt to find examples of such applications.

12.20 Comment on your observations concerning Fig. 12.40.

By the student. The explosion welding operation results in wavy interfaces (as shown in the figures) due to the very high interfacial velocities and pressures involved. The ripples observed are actually due to stress waves in the interface, and help improve joint strength by mechanical interlocking of the mating surfaces. Some students may wish to investigate and elaborate further as to how these waves are developed and how they affect interfacial strength.

12.21 If electrical components are to be attached to both sides of a circuit board, what soldering process(es) would you use? Explain.

A challenging problem arises when a printed circuit board (see Section 13.13) has both surface-mount and in-line circuits on the same board and it is desired to solder all the joints via a reliable automated process. An important point is that all of the in-line circuits should be restricted to insertion from one side of the board. Indeed, there is no performance requirement which would dictate otherwise, but this restriction greatly simplifies manufacturing.

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The basic steps in soldering the connections on such a board are as follows:

(a) Apply solder paste to one side.

(b) Place the surface-mount packages onto the board; also, insert in-line packages through the primary side of the board.

(c) Reflow the solder (see bottom of p. 777).

(d) Apply adhesive to the secondary side of the board.

(e) Attach the surface mount devices on the secondary side, using the adhesive.

(f) Cure the adhesive.

(g) Perform a wave-soldering operation (p. 778) on the secondary side to produce electrical attachment of the surface mounts and the in-line circuits to the board.

12.22 Discuss the factors that influence the strength of (a) a diffusion bonded component and (b) a cold welded component.

Diffusion bonded strength (Section 12.12) is influenced by temperature (the higher the temperature, the more the diffusion), pressure, time, and the materials being joined. The cleanliness of the surfaces is also important to make sure no lubricants, oxides, or other contaminants interfere with the diffusion process. For this reason, these joints are commonly prepared by solvent cleaning and/or pickling to remove oxides. Cold welded components (Section 12.7) involve similar considerations except that temperature is not a relevant parameter.

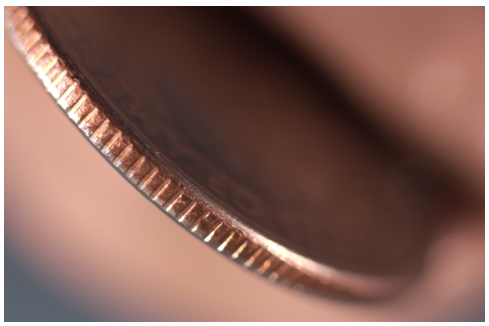
12.23 Describe the difficulties you might encounter in applying explosion welding in a factory environment.

By the student. Explosives are very dangerous; after all, they are generally used for destructive purposes. There are safety concerns such as hearing loss, damage resulting from explosions, and fires. The administrative burden is high because there are many federal, state, and municipal regulations regarding the handling and use of explosives and the registration involved in using explosives.

12.24 Inspect the edges of a U.S. quarter, and comment on your observations. Is the cross-section, i.e., the thickness of individual layers, symmetrical? Explain.

By the student. This is an interesting assignment to demonstrate the significance of cold welding. The side view of a U.S. quarter is shown below. The center of the coin is a copper alloy and the outer layers are a nickel-based alloy. (Note that pennies and nickels are typically made of one material.) The following observations may be made about the coins:

- The core is used to obtain the proper weight and feel, as well as sound.
- The strength of roll-bonded joints is very high, as confirmed by the fact that one never encounters coins that have peeled apart (although during their development such separation did occur).
- The outer layers, which are made of the more expensive alloy, are thin for cost reduction.
- The thicknesses of the two outer layers is not the same. This is due to the smearing action that occurs around the periphery during blanking of the coins, as can be recalled from Section 7.3.



12.25 What advantages do resistance welding processes have over others described in this chapter?

By the student. Recall that resistance welding is a cleaner process for which electrodes, flux, or shielding environment are not needed; the metals to be welded provide all of these inherently. The process is easily automated and production rate is high.

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12.26 What does the strength of a weld nugget in resistance spot welding depend on?

By the student. The students are encouraged to search the literature and collect photographs and more details on weld nuggets (see Fig. 12.33b). This question can be answered from different viewpoints. Thus, for example, one may consider this question as a stress-analysis problem, whereby the joint strength depends on the size of the nugget, its relationship to the surrounding bodies, and the types of materials welded and their mechanical and physical properties. Other factors to be considered are the role of process parameters such as current, pressure, time, and the nature of the faying surfaces. It would also be interesting and instructional to find weld nuggets that are poorly made.

12.27 Explain the significance of the magnitude of the pressure applied through the electrodes during resistance welding operations.

As can be seen in Fig. 12.33, the pressure is applied after sufficient heat is generated. Pressure is maintained until the current is shut off. The higher the pressure, the higher the strength of the joint (although too high a pressure will excessively indent the surfaces and cause damage; see Fig. 12.27). Lower pressures produce weak joints. It should be remembered, however, that the higher the force the lower the resistance, hence the lower the resistance heating. Consequently, proper control of pressure is important in resistance welding.

12.28 Which materials can be friction stir welded, and which cannot? Explain your answer.

Friction stir welding (p. 764) has been commonly applied to aluminum and copper alloys, and some research is being conducted to extend the process to others as well as thermoplastics and reinforced thermoplastics. The main requirements are that the workpiece be sufficiently soft and have a low melting point. The former requirement ensures that the rotating tool (Fig. 12.32) will have appropriate strength for the operation being performed, and the latter to ensure that the power requirements are reasonable.

12.29 List the joining methods that would be suitable for a joint that will encounter high stresses and will need to be disassembled several times during the product life, and rank the methods.

By the student. Refer also to Table 12.1 on p. 733. Disassembly can be a difficult feature to assess when selecting joining methods. If the part has to be disassembled often, bolted connections are likely to be the best solution, or else a quick-disconnect clamp or similar devices should be used. If the number of disassemblies over the lifetime of the part is limited (such as automobile dashboards), integrated snap fasteners (see Fig. 12.55) and even soldering or brazing can be options. However, soldering and brazing are only suitable if the filler metal can be melted without damaging the joint, and if the joint can be resoldered.

12.30 Inspect Fig. 12.31, and explain why the particular fusion-zone shapes are developed as a function of pressure and speed. Comment on the influence of the properties of the material.

By the student. Inspecting the fusion zones in Fig. 12.31, it is obvious that higher forces and speeds both result in more pronounced fusion zones. The relevant material properties are strength at elevated temperatures and physical properties such as thermal conductivity and specific heat. Because all materials soften at elevated temperatures, the hotter the interface, the more pronounced the fusion zone. Note also that a uniform (optimum) zone can be obtained with proper control of the relevant parameters.

12.31 Which applications could be suitable for the roll spot welding process shown in Fig. 12.35c? Give specific examples.

By the student. The roll spot-welding operation, shown in Fig. 12.35, is commonly used to fabricate all types of containers and sheet-metal products. They can be leak proof provided that the spacing of the weld nuggets are sufficiently close.

12.32 Give several examples concerning the bulleted items listed at the beginning of Section 12.1.

By the student. A visit to various stores and observing the products displayed, as well as

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equipment and appliances found in homes, offices, and factories will give ample opportunity for students to respond comprehensively to this question.

12.33 Could the projection welded parts shown in Fig. 12.36 be made by any of the processes described in other parts of this text? Explain.

By the student. The projection-welded parts shown could possibly be made through resistance spot welding (although it would require several strokes) and resistance projection welding. Various other processes may be able to produce the parts shown, but the joint strength developed or the economics of the processes may not be as favorable. The shape can also be achieved through arc or gas welding processes (followed by finishing such as grinding, if necessary), as well as brazing or soldering (see Section 12.13). With a modified interface, mechanical fastening and adhesive bonding also could be suitable processes.

12.34 Describe the factors that influence flattening of the interface after resistance projection welding takes place.

Review Fig. 12.36 and note that:

(a) The projections provide localized areas of heating, so the material in the projection soften and undergo diffusion.

(b) The normal force between the parts flattens these softened projections by plastic deformation.

(c) Important factors are the nature of the mating surfaces, the materials involved, the shape of the projections, the temperatures developed, the magnitude of the normal force, and length of time.

12.35 What factors influence the shape of the upset joint in flash welding, as shown in Fig. 12.37b?

The important factors are the amount of heat generated (if too little heat, the material will not deform to the required extent), the nature of the contracting surfaces (oxide layers, contaminants, etc.), the force applied (the higher the force, the greater the upset volume), the exposed length between the pieces and the clamps (if too long, the part may buckle instead of being upset), thermal conductivity (the lower the conductivity, the smaller the upset length), and the rate at which the force is applied (the higher the rate, the greater the force required for upsetting, due to strain-rate sensitivity of the material at elevated temperatures).

12.36 Explain how you would fabricate the structures shown in Fig. 12.41b with methods other than diffusion bonding and superplastic forming.

By the student. These structures can be made through a combination of sheet-metal forming processes (Chapter 7) and resistance welding, brazing, mechanical joining, or adhesive bonding. Note, however, that such complex parts and interfaces may not allow easy implementation of these various operations without extensive tooling.

12.37 Make a survey of metal containers used for household products and foods and beverages. Identify those that have utilized any of the processes described in this chapter. Describe your observations.

By the student. This is an interesting project for students. It will be noted that some food and beverage containers are three-piece cans, with a welded seam along the length of the can; others may be soldered or seamed (see, for example, Fig. 12.53). These containers are typically used for shaving cream, laundry starch sprays, and various spray cans for paints and other products.

12.38 Which process uses a solder paste? What are the advantages to this process?

Solder paste is used in reflow soldering, described in Section 12.13.3, which is also used for soldering integrated circuits onto printed circuit boards (Section 13.13).

12.39 Explain why some joints may have to be preheated prior to welding.

Some joints may have to be preheated prior to welding in order to:

(a) control and reduce the cooling rate, especially for metals with high thermal conductivity, such as aluminum and copper,

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(b) control and reduce residual stresses developed in the joint, and

(c) for more effective wave soldering (p. 778).

12.40 What are the similarities and differences between casting of metals (Chapter 5) and fusion welding?

By the student. Casting and fusion welding processes are similar in that they both involve molten metals that are allowed to recrystallize, cool, and solidify. The mechanisms are similar in that solidification begins with the formation of columnar grains (Section 5,3). The cooled structure is essentially identical to a cast structure with coarse grains. However, the weld joint (Fig. 12.15) is different in that selection of fillers and heat treatment (after welding) influence the joint's properties.

12.41 Explain the role of the excessive restraint (stiffness) of various components to be welded on weld defects.

Refer to Section 12.6.1. The effect of stiffness on weld defects is primarily through the stresses developed during heating and cooling of the weld joint. Note, for example, that not allowing for contraction (such as due to a very stiff system) will cause cracks in the joint due to high thermal stresses (see Fig. 12.22).

12.42 Discuss the weldability of several metals, and explain why some metals are easier to weld than others.

By the student. This is a challenging assignment and will require considerable effort. Review Section 12.62 and note that, as expected, weldability depends on many factors. See also Table 3.8 and the Bibliography at the end of this chapter.

12.43 Must the filler metal be of the same composition as that of the base metal to be welded? Explain.

It is not necessary for the filler metal, rod, or wire to be the same as the base metal to be welded. Filler metals are generally chosen for the favorable alloying properties that they impart to the weld zone. The only function the filler metal must fulfill is to fill in the gaps in the joint. The filler metal is typically an alloy of the same metal, due to the fact that the workpiece and the filler should melt at reasonably close temperatures. To visualize why this is the case, consider a copper filler used with a material with a much higher melting temperature, such as steel. When the copper melts, the steel workpiece is still in a solid state, and the interface will be one of adhesion, with no significant diffusion between the copper and the steel. (See also bottom of p. 743 and p. 773.)

12.44 Describe the factors that contribute to the difference in properties across a welded joint.

By the student. An appropriate response will require the students to carefully review Section12.6.

12.45 How does the weldability of steel change as the steel's carbon content increases? Why?

By the student. Review Section 12.6.2. As the carbon content increases, weldability decreases because of martensite formation, which is hard and brittle (see p. 238).

12.46 Are there common factors among the weldability, solderability, castability, formability, and machinability of metals? Explain, with appropriate examples.

By the student. This is an interesting, but very challenging, assignment and appropriate for a student paper. As to be expected, the relationships are complex, as can also be seen by reviewing Table 3.8 on p. 117. Note that for some aluminum alloys, for example, machinability and weldability are opposite (i.e., D-C vs. A ratings). The students should analyze the contents of the following: Weldability - Section 12.6.2; solderability - p. 777; castability - Sections 5.4.2 and 5.6; formability - Sections 6.2.6 and 7.7; machinability - Section 8.5.

12.47 Assume that you are asked to inspect a weld for a critical application. Describe the procedure you would follow. If you find a flaw during your inspection, how would you go about determining whether or not this flaw is important for the particular application?

By the student. This is a challenging task, requiring a careful review of Section 12.6.1. Note,

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for example, that visual examination can detect some defects, such as undercuts and toe cracks; however, underbead cracks or incomplete fusion cannot be detected visually. There are nondestructive techniques (Section 4.8) for evaluating a weld, acoustic and X-ray techniques being the most common for determining porosity and large inclusions. Proof stressing a weld is a destructive approach, but it certainly can be suitable since defective welds cannot be placed in service safely.

Some analysis on flaw behavior and crack propagation in metal structures can be attempted, probably with finite-element methods or by using advanced concepts for crack propagation. An understanding of the loads and the resulting stresses often determines whether or not a flaw is important. For example, if the defect in a weld in a beam is at the neutral axis in bending, the flaw is not likely to be critical. On the other hand, a defect in a highly loaded area or in a stress concentration would raise serious concerns.

12.48 Do you think it is acceptable to differentiate brazing and soldering arbitrarily by temperature of application? Comment.

By the student. The definition is somewhat arbitrary. The temperature classification differentiates between the filler metals that can be used in thhe two processes. Note also that, with soldering, thermal distortions are not as critical because of the lower temperatures involved.

12.49 Loctite® is an adhesive used to keep metal bolts from vibrating loose; it basically glues the bolt to the nut once the bolt is inserted in the nut. Explain how this adhesive works.

Loctite® is an anaerobic adhesive (see Table 12.6 on p. 782), meaning that it cures in the absence of oxygen, hence it does not solidify in air. Such a situation exists in the interfaces between threaded fasteners and their nuts, as well as pins and sleeves, so that the adhesive can be applied to the threaded fastener and it does not cure until assembled. The students are encouraged to also review the company literature.

12.50 List the joining methods that would be suitable for a joint that will encounter high stresses and cyclic (fatigue) loading, and rank the methods in order of preference.

By the student. This is a challenging topic where the answers will depend on the workpiece materials that are being considered (see also Table 12.1 on p. 733). Students should not be limited to the answers given here, but should be encouraged to rely upon their experience and training. However, some of the suitable methods for such loadings are:

(a) Riveting is well-suited for such applications, since the rivet can expand upon heading and apply compression to the hole; this can help arrest fatigue cracks.

(b) Bolts can be used for such applications; the use of a preload on a nut can lead to stiff joints with good fatigue resistance.

(c) Welding can be suitable, so long as the weld and the members are properly sized; fatigue crack propogation through the heat-affected zone is a concern.

(d) Brazing can be suitable for such applications, depending on the materials to be brazed.

(e) Adhesive bonding can also be suitable, as long as the joints are properly designed (see Fig. 12.60 on p. 793). The mechanical properties of the adhesive is an important consideration, as well as the strength of bond with the workpiece.

(f) Combinations of these methods are also suitable, such as combining adhesion with riveting as shown in Fig. 12..60d on p. 793.

12.51 Why is surface preparation important in adhesive bonding?

By the student. See Section 12.4.2. Surface preparation is important because the adhesive strength depends greatly on its ability to properly bond to a surface (see also Section 4.5). If, for example, there are lubricant residues on a surface, this ability is greatly hindered. As an example, try sticking masking tape on a dusty, moist or greasy surface, or to your finger coated with a very thin layer of oil or grease.

12.52 Why have mechanical joining and fastening methods been developed? Give several specific examples of their applications.

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By the student. Mechanical joining methods, described in Section 12.15, date back to 3000-2000 B.C., as shown in Table 1.1 on p. 3. These methods have been developed mainly because they impart design flexibility to products, they greatly ease assembly (especially disassembly, thus simplifying repair and part replacement), and have economic advantages.

12.53 Explain why hole preparation may be important in mechanical joining.

By the student. See Section 12.15.1. Note, for example, that if a hole has large burrs (see Fig. 7.5) it can adversely affect joint quality, and also possibly causing crevice corrosion (p. 109). If the hole is significantly larger than the rivet, no compressive stress will be developed on its cylindrical surface when the rivet is upset.

12.54 What precautions should be taken in mechanical joining of dissimilar metals?

By the student. In joining dissimilar metals, one must be careful about their possible chemical interaction. Often, two dissimilar metals react in a cathodic process, causing galvanic corrosion and corrosive wear (see Section 3.9.7). This is especially a concern in marine applications, where sea salt can cause major degradation, as well as in chemical industries.

12.55 What difficulties are involved in joining plastics? What about in joining ceramics? Why?

By the student. See Section 12.16. Plastics can be difficult to join. The thermal conductivity is so low that, if melted, plastics will flow before they resolidify; thermosets will not melt, but will degrade as temperature is increased. Thermoplastics are generally soft and thus cannot be compressed very much in threaded connections, so the bonds with these processes will not be very strong. Thermoplastics are usually assembled with snap fasteners when strength is not a key concern, or with adhesives. Ceramics can be joined by adhesive bonding, and also by mechanical means in which the brittleness and notch sensitivity of these materials are important concerns.

12.56 Comment on your observations concerning the numerous joints shown in the figures in Section 12.17.

By the student. The students may respond to this question in different ways. For example, they can compare and contrast adhesive bonded joints with those of welded and mechanically assembled joints. Note also the projected area of the joints, the type of materials used, their geometric features, and the locations and directions of the forces applied.

12.57 How different is adhesive bonding from other joining methods? What limitations does it have?

By the student. Review Section 12.14. Adhesive bonding is significantly different from other joining methods in that the workpiece materials are of various types, there is no penetration of the workpiece surfaces, and bonding is done at room temperature. Its main limitations are the necessity for clean surfaces, tight clearances, and the longer times required.

12.58 Soldering is generally applied to thinner components. Why?

Solders have much lower strength than braze fillers or weld beads. Therefore, in joining members to be subjected to significant loads, which is typical of members with large thickness, one would normally consider brazing or welding, but not soldering. A benefit of soldering when joining thin components is that it takes place at much lower temperatures than brazing or welding, so that one does not have to be concerned about the workpiece melting due to localized heating, or significant warping in the joint area.

12.59 Explain why adhesively bonded joints tend to be weak in peeling.

Adhesives are weak in peeling because there is a concentrated, high tensile stress at the tip of the joint when being peeled (see Fig. 12.50); consequently, their low tensile strength reduces the peeling forces. (Recall that this situation is somewhat analogous to crack initiation and propagation in metals under tensile stresses; see Fig. 3.30.) Note, however, that tougher adhesives can require considerable force and energy to peel, as can be appreciated when trying to peel off some adhesive tapes.

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12.60 Inspect various household products, and describe how they are joined and assembled. Explain why those particular processes were used.

By the student. Metallic food containers are generally seamed from sheet. Knife blades are often riveted/bonded to their handles. Some pots and pans have a number of cold-welded layers of sheet, which are then deep drawn and formed to desired shapes. The reason pots have a number of layers different materials is to combine their desirable qualities, such as high thermal conductivity of copper with the strength and ease of cleaning of stainless steel. Handles on pots and pans are typically spot welded, riveted, or assembled with threaded fasteners. All of these processes meet functional, technological, economic, or aesthetic requirements.

12.61 Name several products that have been assembled by (a) seaming, (b) stitching, and (c) soldering.

By the student. Note, for example:

(a) Products assembled by seaming are food containers and tops of beverage cans.

(b) Products made through stitching are cardboard and wood boxes, insulation and other construction materials, and footwear.

(c) Soldered parts include electrical components such as diodes attached to circuit boards, pipe fittings, and electrical terminals.

12.62 Suggest methods of attaching a round bar made of thermosetting plastic perpendicularly to a flat metal plate.

By the student. Consider, for example, the following methods:

(a) Threading the end of the rod, drilling and tapping a hole into the plate, and screwing the rod in, using a sealer if necessary.

(b) Press fit.

(c) Riveting the rod in place.

(d) Fittings can be employed.

12.63 Describe the tooling and equipment that are necessary to perform the double-lock seaming operation shown in Fig. 12.53, starting with flat sheet. (See also Fig. 7.23.)

By the student. With some search of the technical literature and the Bibliography given at the end of Chapter 7, the students should be able to describe designs and equipment required for performing this operation.

12.64 What joining methods would be suitable to assemble a thermoplastic cover over a metal frame? Assume that the cover has to be removed periodically.

By the student. Because the cover has to be removed periodically, the most feasible joining method is simply snapping the lid on, as is done on numerous food products (such as polypropylene lids on shortening or coffee cans) which, after opening, can easily be resealed. The sealing is due to the elastic recovery of the lid after it is stretched over the edge of the container. Note, however, that at low temperatures (even in the refrigerator) the lid may crack due to lack of sufficient ductility and severe notch sensitivity of the plastic. The students are encouraged to elaborate further.

12.65 Repeat Question 12.64, but for a cover made of (a) a thermosetting plastic, (b) metal, and (c) ceramic. Describe the factors involved in your selection of methods.

By the student. Consider the following suggestions:

(a) For part (a):
   i. A method similar to Answer 12.64 above, since thermosetting plastics also have some small elastic recovery.
   ii. Some mechanical means.
   iii. Methods would include snap fits.
   iv. Threaded interfaces.

(b) For (b):
   i. Similar to (a) above, especially threaded interfaces, such as screw caps on bottles.

(c) For (c):
   i. The generally low ductility of ceramics would be a significant concern as the cover may crack under repeated

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tensile hoop stresses involved in their use. The students are encouraged to respond to the question as to why a ceramic cover may even be necessary if the container is made of metal.

12.66 Do you think the strength of an adhesively bonded structure is as high as that obtained by diffusion bonding? Explain.

By the student. Because they rely on bond strength, the joint strength in adhesively bonded joints is usually not as high as that achieved through diffusion bonding. Diffusion bonding (Section 12.12) is exceptional in that the two components, typically metals, are diffused into each other, making the joint very strong. Adhesives are generally not as strong as the material they bond (see Table 12.6 on p. 782), unless the materials are inherently weak, such as paper, cardboard, and some plastics. (See also Section 4.4.)

12.67 Comment on workpiece size limitations, if any, for each of the processes described in this chapter.

By the student. This is a good topic for a project. Basically, large parts can be accommodated in these processes by appropriate fixturing. Small parts, on the other hand, may be delicate and thin, hence will require careful handling. Leads for electronic components are generally soldered; the wires are typically much smaller than 1-mm in diameter. (See also Table 12.1 on p. 733.)

12.68 Describe part shapes that cannot be joined by the processes described in this chapter. Gives specific examples.

By the student. A review of the various figures and illustrations in this chapter will clearly indicate that part shape is not a significant difficulty in joining processes. The basic reason is that there is such a very wide variety of processes and possibilities available. The student is encouraged to think of specific illustrations of parts that may negate this statement. In rare cases, if a part shape, as designed, is not suitable for joining with other components, its shape could indeed be modified to enable its assembly with other components (see also design for assembly, Section 14.11).

12.69 Give several applications of electrically conducting adhesives.

By the student. See also Section 12.14.4 where several examples are given.

12.70 Give several applications for fasteners in various household products, and explain why other joining methods have not been used instead.

By the student. The students are encouraged to carefully inspect the variety of products available and to review Sections 12.15, 12.17.4, and 14.10. Note that fasteners are commonly used in many household products, such as coffee makers, electric irons, appliances, furniture, which greatly facilitate assembly, as well as disassembly.

12.71 Comment on workpiece shape limitations, if any, for each of the processes described in this chapter.

By the student. See Question 12.67 and note that it pertained to size limitations, whereas this question concerns shapes. Refer also to design variability in Table 12.1 on p. 733 and welding position in Table 12.2. Although there are some limitations, these are often associated with fixturing requirements. Consider the following: Roll bonding is generally used with sheet metals, so parts that do not involve thin layers are difficult to roll bond. Ultrasonic welding is typically restricted to thin foils. Friction welding requires parts be mounted into chucks or similar fixtures in order to be able to rotate one of the comments to be joined. Spot welding operations can handle complex shapes by appropriate design of electrode holders. Diffusion bonding can produce complex shapes, as can brazing and mechanical fastening.

12.72 List and explain the rules that must be followed to avoid cracks in welded joints, such as hot tearing, hydrogen-induced cracking, lamellar tearing, etc.

By the student. See Section 12.6.1 where all relevant parameters are discussed.

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12.73 If a built-up weld is to be constructed (see Fig. 12.5), should all of it be done at once, or should it be done a little at a time, with sufficient time allowed for cooling between beads?

With proper welding techniques (see also *slag inclusions* in Section 12.6.1) and care, the weld joint can be built continuously, as this procedure will prevent excessive oxidation between bead interfaces, as well as reducing weld time and thus making the process economical.

12.74 Describe the reasons that fatigue failure generally occurs in the heat-affected zone of welds instead of through the weld bead itself.

Fatigue failure and crack propagation (see Sections 2.7 and 3.8) are complex phenomena. Recall that the base metal of the workpiece is often a wrought product with varying degrees of cold work. Thus, the base metal usually has good fatigue resistance. The weld zone itself is highly alloyed, with high strength and also good fatigue resistance. However, the heat affected zone adjacent to the weld does not have the advantageous metallurgy of the weld nor the microstructure of the worked base metal; it has a large grained, equiaxed strucure (see Fig. 12.15 on p. 749). In addition, there is a stress concentration associated with the weld, and the heat affected zone is generally in a volume that is highly stressed. Thus, it is not surprising that the heat affected zone is the usual site of fatigue failure.

12.75 If the parts to be welded are preheated, is the likelihood that porosity will form increased or decreased? Explain.

Weld porosity arises from a number of sources, including micropores (similar to those found in castings; see Section 5.12.1), entrained or evolved gases, and bridging and cracking. If the part is preheated, bridging and cracking are reduced and the cooling rate is lower, therefore large shrinkage pores are less likely. However, since cooling is slower with preheat, soluble gases may be more likely to be entrained unless effective shielding gases are used.

12.76 What is the advantage of electron-beam and laser-beam welding, as compared to arc welding?

The main advantages of these processes are associated with the very small weld zone, and the localized energy input and small heat-affected zone. Weld failures, especially by fatigue, occur in the heat-affected zone; thus, minimizing this volume reduces the likelihood of large flaws and rapid crack growth. Also, the low energy input means that thermal distortions and warping associated with these processes is much lower than with arc welding.

12.77 Describe the common types of discontinuities in welds, explain the methods by which they can be avoided.

By the student. Note that discontinuities in welds are discussed in Section 12.6. Some of the common defects are porosity, inclusions, incomplete fusion/penetration, underfilling, undercutting, overlaps, and cracks. The methods by which they can be avoided are discussed in Section 12.6.1.

12.78 What are the sources of weld spatter? How can spatter be controlled?

Weld spatter arises from a number of sources. If the filler metal is a powder, errant particles can strike the surface and loosely adhere to the surface, similar to the thermal spraying process (pp. 156-157). Even a continuous electrode will spatter, as a violently evolving or pumped shielding gas can cause the molten metal to emit droplets, which then adhere to the workpiece surface near the weld zone.

12.79 Describe the functions and characteristics of electrodes. What functions do coatings have? How are electrodes classified?

By the student. The functions of electrodes include:

(a) Serve as part of the electrical circuit delivering the power required for welding.

(b) Melt and provide a filler metal.

(c) Have a coating or core that provides a shielding gas and flux.

(d) Help stabilize the arc and make the process more robust.

There are many characteristics of electrodes and the student is encouraged to develop an

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appropriate list, noting the two classes of electrodes in arc welding processes: Consumable and nonconsumable. Students will need to perform a literature search to determine classification of electrodes. For example, the following is taken from Hamrock, Schmid, and Jacobson, *Fundamentals of Machine Elements*, 2d ed., McGraw-Hill, 2004.

Electrode number	Ultimate tensile strength, S_u, ksi	Yield strength, S_y, ksi	Elongation, e_k, percent
E60XX	62	50	17-25
E70XX	70	57	22
E80XX	80	67	19
E90XX	90	77	14-17
E100XX	100	87	13-16
E120XX	120	107	14

12.80 Describe the advantages and limitations of explosion welding.

Explosion welding is discussed in Section 12.11. The main advantage is that very dissimilar materials can be bonded, producing high joint strength, as well as specialized applications. The basic limitation is that it is a basically very dangerous operation.

12.81 Explain the difference between resistance seam welding and resistance spot welding.

By the student. The difference between resistance seam welding and resistance spot welding is in the spacing of the weld nuggets (see Sections 12.10.1 and 12.10.2). If the nuggets overlap, it is a seam weld; if they do not overlap, it is a spot weld.

12.82 Could you use any of the processes described in this chapter to make a large bolt by welding the head to the shank? (See Fig. 6.17.) Explain the advantages and limitations of this approach

By the student. Note that processes such as arc welding and gas welding, as well as friction welding, can be used to join the two components. However, the advantage of the latter is that the weld is over the entire contact area between the two joined components, instead of a small bead along the periphery of the contact location. Brazing is another method of joining the two components. The advantages are that unique designs can be incorporated and using different materials; the process is economical for relatively few parts. The limitations are the higher production times required, including subsequent finishing operations, as compared to heading operations, which is a common process for making bolt heads.

12.83 Describe wave soldering. What are the advantages and disadvantages to this process?

Wave soldering, described on p. 778, involves moving a circuit board with inserted components over a stationary wave of solder, as shown in Fig. 12.48. The basic advantage to this process is that it can simultaneously produce a number of high-quality joints inexpensively. The main drawback is that it places restrictions on the layout of integrated circuit packages on a circuit board.

12.84 What are the similarities and differences between a bolt and a rivet?

By the student. Bolts and rivets are very similar in that two or more components are joined by a mechanical means. Both preload the components to function in highly stressed joints. The main difference is that a bolt uses a thread and can thus be disassembled; a rivet is upset and disassembly requires destruction of the rivet.

12.85 It is common practice to tin plate electrical terminals to facilitate soldering. Why is tin a suitable material?

Note in Table 12.5 on p. 777 that solders that are suitable for general purpose and for electronics applications are lead-tin alloys. Thus, the surface tension of the molten solder with the tin plate will be very low, thus allowing good wetting by the solder and resulting in a good joint.

12.86 Review Table 12.3 and explain why some materials require more heat than others to melt a given volume.

Refer to Section 3.9.2. Recall that the melting point of a metal depends on the energy required to separate its atoms, thus it is a characteristic of the individual metal. For an alloy, it depends on the melting points of the individual alloying elements. Additional factors are:

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Problems

12.87 Two flat copper sheets (each 1.5 mm thick) are being spot welded by the use of a current of 7000 A and a current flow time of 0.3 s. The electrodes are 5 mm in diameter. Estimate the heat generated in the weld zone. Assume that the resistance is 200 $\mu\Omega$.

This problem is very similar to Example 12.5 on p. 765. Note in Eq. (12.6) that the quantities now are $I = 7000$ A and $t = 0.3$ s. As in the example, the resistance is 200 $\mu\Omega$. Therefore,

$$H = (7000)^2(0.0002)(0.3) = 2940 \text{ J}$$

As in the example, we take the weld nugget volume to be the projected volume below the electrode, or

$$V = \frac{\pi}{4}d^2t = \frac{\pi}{4}(5)^2(3) = 58.9 \text{ mm}^3$$

From Table 12.3 on p. 737, the specific energy needed to melt copper is $u = 6.1$ J/mm^3. Therefore, the heat needed is

$$H_{\text{melt}} = (58.9)(6.1) = 359 \text{ J}$$

The remaining heat (that is, 2940-359 J = 2581 J) is dissipated into the volume of metal surrounding the weld nugget.

12.88 Calculate the temperature rise in Problem 12.87, assuming that the heat generated is confined to the volume of material directly between the two electrodes and that the temperature distribution is uniform.

The volume of metal directly under the 5-mm electrodes is

$$V = \frac{\pi}{4}d^2t = \frac{\pi}{4}(5)^2(3) = 58.9 \text{ mm}^3,$$

and this volume has a mass of (58.9)(0.00897) = 0.53 g = 0.00053 kg. The specific heat for copper is 385 J/kgK. Therefore, the theoretical temperature rise is

$$\Delta T = \frac{2940 \text{ J}}{(385 \text{ J/kgK})(0.00053 \text{ kg})} = 14,400 \text{ K}$$

Note that the melting point of copper is 1082°C (1355 K), thus much more energy has been provided than is needed for this small volume. Clearly, in practice, very little of the heat is concentrated in this small volume. A more elaborate model of temperature distributions is possible, but beyond the scope of this book. Texts such as Carslaw, H.S., and Jaeger, J.C., *Conduction of Heat in Solids*, Oxford University Press, 1959, address such problems in detail.

12.89 Calculate the range of allowable currents for Problem 12.87, if the temperature should be between 0.7 and 0.85 times the melting temperature of copper. Repeat this problem for carbon steel.

This problem can be interpreted as between 0.7 and 0.85 times the melting temperature on an absolute (Kelvin) or a Celsius temperature scale. This solution will use a Celsius scale, so that the final target temperature is between 765 and 925 °C. Using the same approach as in Problem 12.87, the allowable energy for these cases is 100 and 121 J, respectively. With a resistance of 200 $\mu\Omega$, the currents are 1310 and 1420 A, respectively. The solution for carbon steel is left for the student to supply, but uses the same approach.

12.90 In Fig. 12.24, assume that most of the top portion of the top piece is cut horizontally with a sharp saw. Thus, the residual stresses will be disturbed, and, as described in Section 2.10, the part will undergo shape change. For this case, how will the part distort? Explain.

Inspecting Fig. 12.24 and recalling Answer 2.25 regarding Fig. 2.30, we arrive at the following observations and conclusions: (1) The top portion of the top piece is subjected to longitudinal compressive residual stresses. (2) If we cut this portion with a sharp saw (so that we do not induce further residual stresses during cutting), stresses will rearrange themselves and the part will bend downward, i.e., it will hold water, assuming it will not warp in the plane of the page. For details, recall the spring analogy in Problem 2.25.

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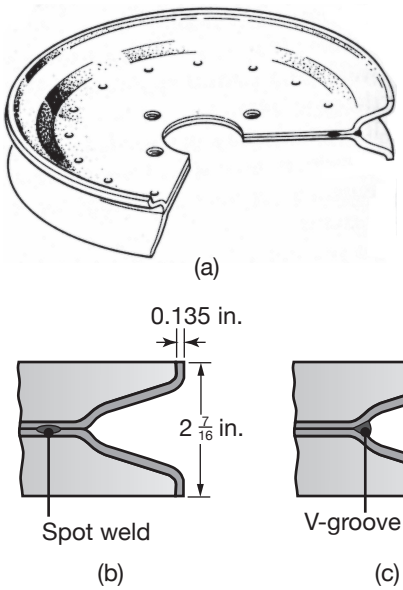
12.91 The accompanying figure shows a metal sheave that consists of two matching pieces of hot-rolled, low-carbon-steel sheets. These two pieces can be joined either by spot welding or by V-groove welding. Discuss the advantages and limitations of each process for this application.



By the student. The original method of joining the two sheaves was by resistance spot welding, with 16 welds equally spaced around the periphery, as shown in (b). Although the weld quality was satisfactory, the welding time per sheave was 1 minute. In order to increase production rate, an alternative process was chosen (gas-metal-arc welding, GMAW) with a continuous weld around the periphery of the sheave as shown in (c). With an automated welding process, the welding time per sheave was reduced to 40 s.

12.92 A welding operation takes place on an aluminum-alloy plate. A pipe 50-mm in diameter with a 4-mm wall thickness and a 60-mm length is butt-welded onto a section of 15 x 15 x 5 mm angle iron. The angle iron is of an L-shape and has a length of 0.3 m. If the weld zone in a gas tungsten-arc welding process is approximately 8 mm wide, what would be the temperature increase of the entire structure due to the heat input from welding only? What if the process were an electron-beam welding operation with a bead width of 6 mm? Assume that the electrode requires 1500 J and the aluminum alloy requires 1200 J to melt one gram.

For the first part of the problem, assume that the electrode is placed around the entire pipe, so that the weld length is $\pi D = \pi(50 \text{ mm}) = 0.157$ m. If the weld cross section is triangular, its volume is approximately

$$V = \frac{1}{2}bhL = \frac{1}{2}(0.008 \text{ m})^2(0.157 \text{ m})$$

or $V = 5.02 \times 10^{-6}$ m^3 $= 5020$ mm^3. The electrode material should be matched to aluminum, so it will likely be an aluminum alloy in order to approximately match melting temperatures and compatibility. The density should therefore be around 2700 kg/m^3 (see Table 3.3 on p. 106, where it is also noted that $C = 900$ J/kg-K). The specific heat to melt aluminum alloys is given by Table 12.3 as 2.9 J/mm^3. Therefore, the energy input is $(2.9)(5020) = 14.5$ kJ. The total volume of the aluminum is

$$\begin{aligned} V &= \frac{\pi}{4}(d_o^2 - d_i^2)L + 2btl \\ &= \frac{\pi}{4}(50^2 - 42^2)(60) + 2(15)(5)(300) \\ &= 79,683 \text{ mm}^3 \end{aligned}$$

or $V = 7.968 \times 10^{-5}$ m^3. The temperature rise is then calculated as:

$$E = \rho V C \, \Delta T$$

Solving for ΔT,

$$\begin{aligned} \Delta T &= \frac{E}{\rho V C} \\ &= \frac{14,500}{(2700)(7.968 \times 10^{-5})(900)} \end{aligned}$$

Or $\Delta T = 75°$C. For the second part of the problem, the change to be made is in the input energy. Using the same approach as above, we have

$$V = \frac{1}{2}bhL = \frac{1}{2}(0.006 \text{ m})^2(0.157 \text{ m})$$

or $V = 2.826 \times 10^{-6}$ m^3=2826 mm^3. The input energy is (2.9)(2826)=8.20 kJ. The temperature rise is therefore

$$\begin{aligned} \Delta T &= \frac{E}{\rho V C} \\ &= \frac{8200}{(2700)(7.968 \times 10^{-5})(900)} \\ &= 42°\text{C} \end{aligned}$$

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12.93 A shielded metal arc welding operation is taking place on carbon steel to produce a fillet weld (see Fig. 12.21b). The desired welding speed is around 25 mm/sec. If the power supply is 10 V, what current is needed if the weld width is to be 7 mm?

Since its width is 7 mm, the cross-sectional area of the weld is $A = \frac{1}{2}(7 \text{ in}^2) = 24.5 \text{ mm}^2 = 2.45 \times 10^{-5} \text{ m}^2$. For shielded metal arc welding, we obtain from Section 12.3.1 that $C = 75\%$. From Table 12.3, u is assigned a mean value of 9.7 J/mm^3. From Eq. (12.5), the weld speed is therefore calculated as

$$v = e\frac{VI}{uA}$$

Solving for the current, I,

$$I = \frac{uvA}{eV} = \frac{(9.7)(25)(24.5)}{(0.75)(10)}$$

or $I = 792$ A.

12.94 The energy applied in friction welding is given by the formula $E = IS^2/C$, where I is the moment of inertia of the flywheel, S is the spindle speed in rpm, and C is a constant of proportionality (5873, when the moment of inertia is given in lb-ft^2). For a spindle speed of 600 rpm and an operation in which a steel tube (3.5 in. OD, 0.25 in. wall thickness) is welded to a flat frame, what is the required moment of inertia of the flywheel if all of the energy is used to heat the weld zone (approximated as the material 0.25 in. deep and directly below the tube)? Assume that 1.4 ft-lbm is needed to melt the electrode.

The flywheel moment of inertia can be calculated as:

$$E = \frac{IS^2}{C}$$

Solving for I,

$$I = \frac{EC}{S^2} = \frac{(1.4)(5873)}{(600)^2} = 0.0228 \text{ lb-ft}^2$$

12.95 In oxyacetylene, arc, and laser-beam cutting, the processes basically involve melting of the workpiece. If an 80 mm diameter hole is to be cut from a 250 mm diameter, 12 mm thick plate, plot the mean temperature rise in the plate as a function of kerf. Assume that one-half of the energy goes into the plate and one-half goes into the blank.

The volume melted is

$$V = (\pi D)th = \pi(80 \text{ mm})(12 \text{ mm})t = 30106t$$

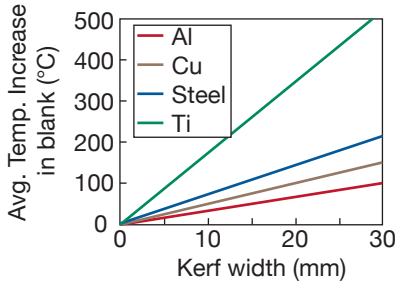
where t is the kerf width in mm. The energy input is then $E = uV/2 = 1508ut$, where u is the specific energy required to melt the workpiece, as given in J/mm^3 in Table 12.1. Note that we have divided the energy by two because only one-half of the energy goes into the blank. The volume of the blank is

$$\begin{aligned} V &= \frac{\pi}{4}d^2h \\ &= \frac{\pi}{4}\left[(250 \text{ mm})^2 - (80 \text{ mm})^2\right](12 \text{ mm}) \\ &= 5.29 \times 10^{-4} \text{ m}^3 \end{aligned}$$

The temperature rise in the blank is $\Delta T = E/\rho V C_p$; substituting for the input energy,

$$\begin{aligned} \Delta T &= \frac{1508ut}{\rho C_p(5.29 \times 10^{-4})} \\ &= (2.85 \times 10^6)t\left(\frac{u}{\rho C_p}\right) \end{aligned}$$

It can be seen that the plot of temperature rise is a linear function of width, t. This is plotted below for selected materials.



12.96 Refer to the simple butt and lap joints shown in Fig. 12.1. (a) Assuming the area of the butt joint is 3 mm × 20 mm and referring to the adhesive properties given in Table 12.6, estimate the minimum and maximum tensile force that this joint can withstand. (b) Estimate these forces for the lap joint assuming its area is 15 mm × 15 mm.

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Referring to Table 12.6 on p. 782, note that the lowest adhesive strength is for epoxy or polyurethane at 15.4 MPa, and the highest tension-shear strength is for modified acrylic at 25.9 MPa. These values are used in the solution below.

(a) For a butt joint, assuming there is strong adhesion between the adhesive and workpiece, the full strength of the adhesive can be developed. In this case, we can calculate the required load-bearing area as

$$A = (3)(20) = 60 \text{ mm}^2 = 6.0 \times 10^{-5} \text{ m}^2$$

Consequently, we have

$$F_{\min} = (15.4 \times 10^6)(6.0 \times 10^{-5}) = 924 \text{ N}$$

and

$$F_{\max} = (25.9 \times 10^6)(6.0 \times 10{-}5) = 1554 \text{ N}$$

(b) For the lap joint, we similarly obtain $A = (15)(15) = 225 \text{ mm}^2 = 2.25 \times 10^{-4} \text{ m}^2$. Note that in this case, the joint is loaded in shear, and the shear strength is one-half the tensile strength, as discussed in courses on mechanics of solids. Therefore,

$$F_{\min} = \frac{1}{2}\left(15.4 \times 10^6\right)\left(2.25 \times 10^{-4}\right)$$

or $F_{\min} = 1730$ N. Also,

$$F_{\max} = \frac{1}{2}\left(25.9 \times 10^6\right)\left(2.25 \times 10^{-4}\right)$$

or $F_{\max} = 2910$ N.

12.97 As shown in Fig. 12.61, a rivet can buckle if it is too long. Using information from solid mechanics, determine the length-to-diameter ratio of a rivet that will not buckle during riveting.

The riveting process is very similar to heading (see Section 6.2.4). Basically, the design requirement is that the length-to-diameter ratio should be 3 or less. If the heading tool has a controlled geometry, a longer length can be accommodated if the head diameter is not more than 1.5 times the shank diameter.

12.98 Repeat Example 12.2 if the workpiece is (a) magnesium, (b) copper or (c) nickel.

(a) For the magnesium workpiece, Table 12.3 gives $u = 2.9$ J/mm^3. Therefore, from Eq. (12.5),

$$v = e\frac{VI}{uA} = (0.75)\frac{(20)(200)}{(2.9)(30)} = 34.5 \text{ mm/s}.$$

(b) For the copper workpiece, we have $u = 6.1$ J/mm^3. Therefore, from Eq. (12.5),

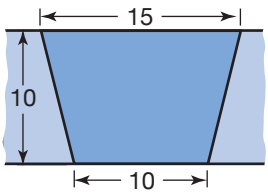
$$v = e\frac{VI}{uA} = (0.75)\frac{(20)(200)}{(6.1)(30)} = 16.4 \text{ mm/s}.$$

(c) For the nickel workpiece, we have $u = 9.8$ J/mm^3. Therefore, from Eq. (12.5),

$$v = e\frac{VI}{uA} = (0.75)\frac{(20)(200)}{(9.8)(30)} = 10.2 \text{ mm/s}.$$

12.99 A submerged arc welding operation takes place on 10 mm thick stainless steel, producing a butt weld as shown in Fig. 12.20c. The weld geometry can be approximated as a trapezoid with 15 mm and 10 mm as the top and bottom dimensions, respectively. If the voltage provided is 40 V at 400 A, estimate the welding speed if a stainless steel filler wire is used.

A sketch of the weld cross section is shown below.



The area of the trapezoid is

$$A = (10)(10) + 2\left(\frac{1}{2}\right)(2.5)(10) = 125 \text{ mm}^2$$

For submerged arc welding, it is stated in Section 12.3.1 that $e = 0.90$. For a stainless steel workpiece, the unit specific energy is obtained from Table 12.3 as $u = 9.4$ J/mm^3. Therefore, from Eq. (12.5),

$$\begin{aligned} v &= e\frac{VI}{uA} \\ &= 0.9\frac{(40)(400)}{(9.4)(125)} \\ &= 12.2 \text{ mm/s} \end{aligned}$$

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12.100 Assume that you are asked to give a quiz to students on the contents of this chapter. Prepare three quantitative problems and three qualitative questions, and supply the answers.

By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

Design

12.101 Design a machine that can perform friction welding of two cylindrical pieces, as well as remove the flash from the welded joint. (See Fig. 12.30.)

By the student. Note that this machine can be very similar to a lathe, where one-half of the workpiece is held in a fixture attached to the tailstock, the other half is in the rotating chuck, and a cutting tool is used as in turning.

12.102 How would you modify your design in Problem 12.101 if one of the pieces to be welded is non-circular?

By the student. The machine is more complicated, machining can become more difficult, with essentially a milling operation taking place after welding.

12.103 Describe product designs that cannot be joined by friction welding processes.

By the student. Consider, for example, that if one of the components is a very thin tube, it will not be able to support the large axial loads involved in friction welding; likewise, if the other component is very think and slender.

12.104 Make a comprehensive outline of joint designs relating to the processes described in this chapter. Give specific examples of engineering applications for each type of joint.

By the student. Refer to Section 12.17. This is a challenging problem, and would be suitable for a project or a paper.

12.105 Review the two weld designs in Fig. 12.58a, and, based on the topics covered in courses on the strength of materials, show that the design on the right is capable of supporting a larger moment, as shown.

The problem statement assumes that the failure in the part on the left will be in the weld itself; if the material strength determines the moment that can be supported, then the weld design is irrelevant. Assuming that the weld zone is roughly square, it is better to place the welds as shown on the right because the strength arises from the cube of the distance from the neutral axis. In the design on the left, only the extreme ends are fully loaded, and some material (at the neutral axis) is subjected to very little stress.

12.106 In the building of large ships, there is a need to weld large sections of steel together to form a hull. For this application, consider each of the welding operations described in this chapter, and list the benefits and drawbacks of that operation for this product. Which welding process would you select? Why?

By the student. This specialized topic is very suitable for a student paper, requiring a search of the technical literature in shipbuilding technologies. For example, the following may be suggested:

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Process	Advantages	Disadvantages
Oxyfuel	Inexpensive; portable.	Significant joint distortion; welding of thick sections is difficult.
SMAW	Inexpensive; portable.	Thick sections need a built-up weld (see Fig. 12.5 on p. 738), possibly compromising joint strength.
SAW	Good weld strength; can be automated	Limited workspace; workpiece must be horizontal, a difficult restriction for boat hulls
ESW	Good weld strength, well-suited for vertical welds.	More complicated equipment required.

12.107 Examine various household products, and describe how they are joined and assembled. Explain why those particular processes are used for these applications.

By the student. Consider the following: Metallic food containers that are seamed from sheet. Knife blades that are riveted/bonded to their handles. Pots with a number of cold-welded layers of sheet, which are then deep drawn and formed to desired shapes. All of these processes are used because other processes which are technologically feasible may lack economic, functional, or aesthetic advantages.

12.108 A major cause of erratic behavior (hardware bugs) and failure of computer equipment is fatigue failure of the soldered joints, especially in surface-mount devices and devices with bond wires. (See Fig. 12.48.) Design a test fixture for cyclic loading of a surface-mount joint for fatigue testing.

By the student. This is a very demanding project, and can be expanded into a group design project. Students can consider if the test should duplicate the geometry of a surface mount or if an equivalent geometry can be analyzed. They can determine loading cycle durations and amplitudes, as well as various other test parameters.

12.109 Using two strips of steel 1 in. wide and 8 in. long, design and fabricate a joint that gives the highest strength in a tension test in the longitudinal direction.

By the student. This is a challenging problem and an experimental project, as well; it could also be made into a contest among students in class. It must be noted, however, that the thickness of the strips is not given in the statement of the problem (although the word strip generally indicates a thin material). The thickness is a factor that students should recognize and comment on, and supply their answers accordingly. It can also be seen that most of the processes described in Chapter 12 can be used for such a joint. Consequently, a wide variety of processes and designs should be considered, making the response to this question extensive.

In using a single bolt through the two strips, for example, it should be apparent that if the bolt diameter is too large, the stresses in the rest of the cross section may be too high, causing the strips to fail prematurely. If, on the other hand, the bolt diameter is too small, it will easily shear off under the applied tensile force. Thus, there has to be an optimum to bolt size. The students are encouraged to consider multiple-bolt designs, as well as a host of other processes either singly or in combination.

12.110 Make an outline of the general guidelines for safety in welding operations. For each of the operations described in this chapter, prepare a poster which effectively and concisely gives specific instructions for safe practices in welding (or cutting). Review the various publications of the National Safety Council and other similar organizations.

By the student. This is a valuable study by the students, and the preparation of a poster or a flyer is a good opportunity for students. Safety in Welding is a standard published by the American National Standards Institute (ANSI Z49.1) and describes in detail the safety precautions that must be taken. Most of the standards are process-specific. As an example, some safety guidelines for shielded metal-arc welding are:

- The operator must wear eye and skin pro-

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tection against radiation.

- Leather gloves and clothing should be worn to prevent burns from arc spatter.
- Welding should be done in properly ventilated areas, where fresh air is available to workers and the work area is not flooded by shielding gases.
- To prevent electric shock, the welder should not weld while standing on a wet surface.
- The workpiece should be positioned to minimize trauma to the back and arms.

12.111 A common practice for repairing expensive broken or worn parts, such as may occur when, for example, a fragment is broken from a forging, is to fill the area with layers of weld bead and then to machine the part back to its original dimensions. Make a list of the precautions that you would suggest to someone who uses this approach.

By the student. Considerations are that the interface between the forging and the filling may not have sufficient strength. The weld bead will have different properties than the substrate (the forging) and have an uneven surface, thus machining may result in vibration and chatter. The weld material may cause the cutting tools to wear more rapidly. The weld may fracture during machining and compromise part integrity. The weld material may have insufficient ductility and toughness for the application.

12.112 In the roll bonding process shown in Fig. 12.28, how would you go about ensuring that the interfaces are clean and free of contaminants, so that a good bond is developed? Explain.

By the student. The students are encouraged to perform a literature search for particular approaches. The basic procedure has been (a) wire brushing the surfaces, which removes oxide from the surfaces, and (b) solvent cleaning, which removes residues and organic films from the surface. (See also Section 4.5.2.)

12.113 Alclad stock is made from 5182 aluminum alloy, and has both sides coated with a thin layer of pure aluminum. The 5182 provides high strength, while the outside layers of pure aluminum provide good corrosion resistance, because of their stable oxide film. Alclad is commonly used in aerospace structural applications for these reasons. Investigate other common roll bonded materials and their uses, and prepare a summary table.

By the student. This topic could be a challenging project for students. Examples include coinage (see also Question 12.24) and a thin coating of metals on workpieces where the coating serves as a solid lubricant in metalworking (see p. 152).

12.114 Obtain a soldering iron and attempt to solder two wires together. First, try to apply the solder at the same time as you first put the soldering iron tip to the wires. Second, preheat the wires before applying the solder. Repeat the same procedure for a cool surface and a heated surface. Record your results and explain your findings.

By the student. This is a valuable and inexpensive laboratory experience, showing the importance of surface tension. With cold wires, molten solder has high surface tension against the wires, and thus the solder does not wet the surface. At elevated temperatures, the solder has low surface tension and the solder coats the wire surfaces very effectively. Students can be asked to examine this phenomenon further by placing a small piece of solder of known volume (which can be measured with a precision scale) on a steel plate section. When heated, the solder spreads according to the surface temperature of the steel. It will be noted that above a threshold value, the solder will flow freely and coat the surface.

12.115 Perform a literature search to determine the properties and types of adhesives used to affix artificial hips onto the human femur.

By the student. Sometimes an adhesive is used, but with some designs this is not necessary, as they rely upon *osteointegration* or bone-ingrowth to affix the implant. Usually the cement is polymethylmethacrylate, an acrylic polymer often referred to as bone cement, or else a hydroxyapetite polymer is used. New materials are constantly being developed and

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a number of variations can be found in the literature and through an Internet search. A common trend is to develop cements from calcium phosphates, as these are closer matches to the mineral content of bone.

12.116 Using the Internet, investigate the geometry of the heads of screws that are permanent fasteners (that is, ones that can be screwed in but not out).

By the student. These heads usually present a straight vertical surface for the screwdriver in one direction, but a curved surface in the opposite direction, so that a screwdriver simply slips when turned counterclockwise and is not effective for unscrewing. The sketch on the left was obtained from www.k-mac-fasteners.com, while the photo on the right was obtained from www.storesonline.com.

12.117 Obtain an expression similar to Eq. (12.6), but for electron beam and laser welding.

By the student. The heat input is generally given by

$$H = cIA$$

where c is a constant that indicates the portion of laser energy absorbed by the material, and I is the intensity of light over the area A.

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Chapter 13

Fabrication of Microelectronic, Micromechanical, and Microelectromechanical Devices; Nanomanufacturing

Questions

13.1 Define the terms *wafer, chip, device, integrated circuit,* and *surface mount.*

A wafer is a slice of a thin cylinder of silicon. A chip is a fragment of a wafer. A device is either a (1) micromechanical arrangement without any integrated electronic circuitry or a (2) simple electronic element such as a transistor. An integrated circuit is a semiconductor-based design, incorporating large amounts of electronic devices.

13.2 Why is silicon the most commonly used semiconductor in IC technology? Explain.

The reason is its unique capabilities regarding the growth of oxides and deposition of metal coatings onto the oxides, so that metal on oxide semiconductors can be easily fabricated.

13.3 What do the terms VLSI, IC, CVD, CMP, and DIP stand for?

VLSI - Very large scale integration; IC - integrated circuit; CVD - chemical vapor deposition; CMP - chemical mechanical planarization or chemical mechanical polishing; DIP - dual in-line package.

13.4 How do n-type and p-type dopants differ? Explain.

The difference is whether or not they donate or take an electron from the (usually) silicon into which they are doped.

13.5 How is epitaxy different than other forms of film deposition?

Epitaxial layers are grown from the substrate, as described in Section 13.5. Other films are externally applied without consuming the substrate.

13.6 Comment on the differences between wet and dry etching.

Wet etching involves liquid-based solutions into which the workpiece is immersed. The process is usually associated with high etch rates and isotropic etch patterns, and is relatively easy to mask. Dry etching usually involves placing the workpiece into a chamber with gas or plasma, and the plasma drives the etching process. The process is usually associated with low etch rates and anisotropic etching, and is more difficult to mask.

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13.7 How is silicon nitride used in oxidation?

As described on in Section 13.6, silicon nitride is used for selective oxidation, since silicon nitride inhibits the passage of oxygen and water vapor. Thus, the silicon nitride acts as a mask in oxidation.

13.8 What are the purposes of prebaking and postbaking in lithography?

As described on p. 817, prebaking of wafers is done (prior to lithography) to remove solvent from the photoresist, and to harden the photoresist. After lithography, the wafer is postbaked to improve the adhesion of the remaining photoresist.

13.9 Define selectivity and isotropy and their importance in relation to etching.

Selectivity describes the preferential etching of some materials over others with a given etchant. Isotropy describes the rate of etching in different directions relative to the surface. These are important with respect to etching because to obtain high-quality integrated circuits, good definition and closely packed devices are needed. This requires and understanding of both selectivity and isotropy in etching.

13.10 What do the terms *linewidth* and *registration* refer to?

Linewidth (p. 818) is the width of the smallest feature obtainable on the silicon surface. Current minimum linewidths are around 0.13 μm. Registration refers to alignment of wafers in lithography. Both of these are interrelated, since highly resolved integrated circuits cannot be obtained unless the linewidth is sufficiently small and the registration is performed properly.

13.11 Compare diffusion and ion implantation.

Diffusion and ion implantation are similar. Diffusion refers to the process of atom migration, and is closely related to temperature. Ion implantation involves accelerating ions and directing them to a surface where they are incorporated. Thus, both diffusion and ion implantation can be used to drive dopants into semiconductor materials.

13.12 What is the difference between evaporation and sputtering?

In evaporation, the coating is heated until it is a vapor, which then deposits from vapor phase onto the cooler workpiece surface. In sputtering, ions impact the coating material and cause atoms to be ejected or sputtered. These atoms then condense on the workpiece. A further description is in Section 4.5.1.

13.13 What is the definition of yield? How important is yield? Comment on its economic significance.

Yield is the ratio of functional chips to the number of chips produced. Obviously, yield is extremely important because of its major influence on the economics of chip manufacture.

13.14 What is accelerated life testing? Why is it practiced?

In accelerated life testing, the test subject is exposed to a harsher environment than its working environment. For example, the test subject may be exposed to higher temperatures, higher stresses, or higher temperature variations. The time until failure is then measured, and inferences are made as to its expected life in the working environment. Accelerated life testing is essential because many products last a very long time, and thus it would not be practical to test under normal conditions.

13.15 What do BJT and MOSFET stand for?

BJT: Bipolar junction transistor, and MOSFET: Metal on oxide field effect transistor.

13.16 Explain the basic processes of (a) surface micromachining and (b) bulk micromachining.

In surface micromachining, the selectivity of wet etching is exploited to produce small mechanical features on silicon or on other surfaces. As shown in Fig. 13.34, surface micromachining involves production of a desired feature through film deposition and etching; a spacer layer is then removed through wet etching, where the spacer layer is easily etched while the structural material is not etched.

13.17 What is LIGA? What are its advantages over other processes?

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LIGA is an acronym from the German terms X ray *Lithographie*, *Galvanoformung und Abformung*, or x-ray lithography, electroforming and molding, as shown in Fig. 13.44 on p. 852. LIGA has the capability of producing MEMS and micromechanical devices with very large aspect ratios. The operation also allows the production of polymer MEMS devices and the mass production of MEMS devices, since the LIGA-produced structure is a mold for further processing.

13.18 What is the difference between isotropic and anisotropic etching?

In isotropic etching, material is chemically machined in all directions at the same rate, as shown in Fig. 13.17a on p. 824. Anisotropic etching involves chemical machining where one direction etches faster than another, with the extreme being vertical etching (Fig. 13.23f on p. 831) where material is only removed in one direction.

13.19 What is a mask? What is its composition?

A mask is a protective layer that contains all of the geometric information desired for an etching or ion implantation step; it can be considered to be a protective coating. Masking prevents machining where the mask is present. A mask can be produced from a variety of materials, although typically they are polymers.

13.20 What is the difference between chemically assisted ion etching and dry plasma etching?

As described in Section 13.8.2, chemically assisted ion etching is one type of dry etching. Dry etching involves etching in a plasma, and chemically assisted ion etching uses chemical reactive species in the plasma to remove material, and the ion bombardment is used to help remove the chemical species attached to the surface.

13.21 Which process(es) in this chapter allow(s) fabrication of products from polymers? (See also Chapter 10.)

By the student. It will be noted that polymers are most easily produced from LIGA and solid freeform fabrication processes. They can be produced through surface micromachining, but in practice, it is very difficult because of the presence of surface residual stresses and the lack of high selectivity in etchants.

13.22 What is a PCB?

PCB is a printed circuit board (see Section 13.13).

13.23 With an appropriate sketch, describe the thermosonic stitching process.

As shown in Fig 13.28 on p. 836, in thermosonic stitching, a gold wire is welded to a bond pad on a printed circuit board. The wire is then fed from a spool through a nozzle, so that a wire thread' is stretched to a lead on the integrated circuit package. The gold wire is then thermosonically welded to the package, similar to ultrasonic welding described in Section 12.7.

13.24 Explain the difference between a die, a chip, and a wafer.

A die is a completed integrated circuit. A chip is the portion of the wafer used to construct integrated circuits. A wafer is a slice of a single crystal silicon cylinder. It should be noted that there are many dice on a chip, and a chip is part of a wafer.

13.25 Why are flats or notches machined onto silicon wafers? Explain.

The flats are machined to assist in registration, and to also indicate the crystallographic orientation of the silicon in the wafer. Anisotropic etching processes require that designers account for the crystallographic orientation.

13.26 What is a via? What is its function?

A via is an electrical connections between layers of a printed circuit board, as depicted in Fig. 13.31 on p. 840. With a large number of circuits on a board, it is clear that the required electrical connections are very difficult to make if all of the connections must lie within a single plane. A via allows the designer to make electrical connections on a number of planes, thus greatly simplifying layout on a board.

13.27 What is a flip chip? Describe its advantages over a surface-mount device.

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A flip chip, shown in Fig. 13.30 on p. 838, has a large number of solid metal balls that mate to bond pads on the printed circuit board. It gets its name from the process used to remove the chip from its supply tape and assembling it to the circuit board. The main advantage of a flip chip over a surface mount device is that a larger number of connections can be made on a smaller area, allowing a greater density of integrated circuits on a printed circuit board.

13.28 Explain how IC packages are attached to a printed circuit board if both sides will contain ICs.

If both sides are to contain ICs, the designer must first make sure that all through-hole mount packages are placed on one side of the board. This same side will then have all remaining components attached through reflow (paste) soldering. The opposite side of the board will have components glued in place and then a wave soldering operation takes place.

13.29 In a horizontal epitaxial reactor (see the accompanying figure), the wafers are placed on a stage (susceptor) that is tilted by a small amount, usually 1°-3°. Why is this procedure done?

The stage in the horizontal epitaxial reactor is usually tilted by a small amount to provide equal amounts of reactant gases in both the front and back of the chamber. If the stage is not tilted, the reactant gases would be partially used up (on the wafers in the front of the chamber) before they reach the wafers at the back end of the chamber, causing nonuniformities in the film deposited.

13.30 The accompanying table describes three changes in the manufacture of a wafer: increase of the wafer diameter, reduction of the chip size, and increase of the process complexity. Complete the table by filling in the words increase, decrease, or no change to indicate the effect that each change would have on wafer yield and on the overall number of functional chips.

Effects of manufacturing changes		
Change	Wafer yield	Number of functional chips
Increase wafer diameter		
Reduce chip size		
Increase process complexity		

The completed table is shown below:

Effects of manufacturing changes		
Change	Wafer yield	Number of functional chips
Increase wafer diameter	No change	Increase
Reduce chip size	Increase	Increase
Increase process complexity	Decrease	Decrease

13.31 The speed of a transistor is directly proportional to the width of its polysilicon gate, with a narrower gate resulting in a faster transistor and a wider gate resulting in a slower transistor. Knowing that the manufacturing process has a certain variation for the gate width, say ± 0.1 μm, how might a designer alter the gate size of a critical circuit in order to minimize its speed variation? Are there any penalties for making this change? Explain.

In order to minimize the speed variation of critical circuits, gate widths are typically designed at larger than the minimum allowable size. As an example, if a gate width is 0.5 μm and the process variation is ± 0.1 μm, a $\pm 20\%$ variation in speed would be expected. However, if the gate width is increased to 0.8 μm, the speed variation reduces to $\pm 12.5\%$. The penalty for this technique is a larger transistor size (and, in turn, a larger die area) and also a slower transistor.

13.32 A common problem in ion implantation is channeling, in which the high-velocity ions travel

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deep into the material through channels along the crystallographic planes before finally being stopped. What is one simple way to stop this effect?

A simple and common method of stopping ion channeling during implantation is to tilt the crystal material by a few degrees (4-7°) so that the incident ion beam is not coincident with the crystallographic planes of the material.

13.33 The MEMS devices described in this chapter use macroscale machine elements, such as spur gears, hinges, and beams. Which of the following machine elements can or cannot be applied to MEMS, and why?

(a) ball bearing;

(b) helical springs;

(c) bevel gears;

(d) rivets;

(e) worm gears;

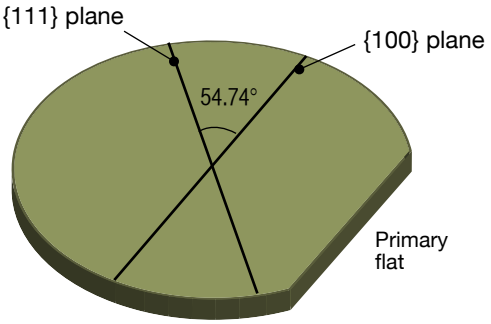
(f) bolts;

(g) cams.

All of the devices can be manufactured, but ball bearings, helical springs, worm gears, and bolts are extremely difficult to manufacture, as well as use, in micromechanical systems. The main reason these components cannot be easily manufactured is that they are three dimensional, whereas the MEMS manufacturing processes, as currently developed, are best suited for 2D, or at most, $2\frac{1}{2}$D devices.

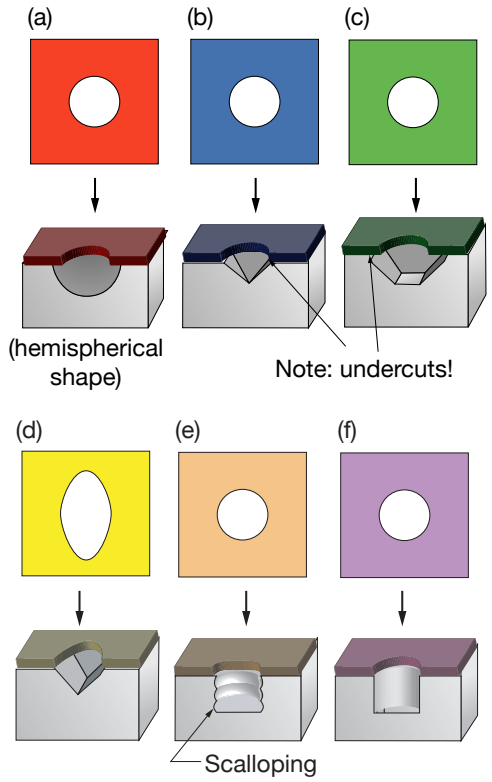
13.34 Figure 13.7b shows the Miller indices on a wafer of (100) silicon. Referring to Fig. 13.5, identify the important planes for the other wafer types illustrated in Fig. 13.7a.

The crystal orientation doesn't depend on whether the silicon is n- or p-type, so that what is shown in part (b) fits equally well for either {100} wafer. The proper structure for a {111} type is as follows:



13.35 Referring to Fig. 13.23, sketch the holes generated from a circular mask.

The challenge to this problem is that conical sections are difficult to sketch. Note, however, that some etching processes will expose crystallographic planes, resulting in an undercut of the circular mask in places. The sketches are given below:



13.36 Explain how you would produce a spur gear if its thickness were one tenth its diameter and its diameter were (a) 10 μm, (b) 100 μm, (c) 1 mm, (d) 10 mm, and (e) 100 mm.

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The answer depends on the material, but lets assume the material is silicon.

(a) 10-μm spur gear could be produced through surface micromachining.

(b) 100 μm spur gear could be produced through micromachining; if silicon is not the desired material, LIGA is also an option.

(c) 1-mm gear can be produced through LIGA, chemical blanking, or chemical etching from foil.

(d) 10 mm gear can be blanked or chemically blanked.

(e) 100 mm gear could best be machined (see Section 8.10.7).

13.37 Which clean room is cleaner, a Class-10 or a Class-1?

Recall that the class of a clean room is defined as the number of 0.5 μm or larger particles within a cubic foot of air (see Section 13.2). Thus, a Class-1 room is cleaner than a Class-10 room.

13.38 Describe the difference between a microelectronic device, a micromechanical device and MEMS.

By the student. A microelectronic device is any integrated circuit. Literally, the device is microscale, so that a microscope is needed to see this device, but practically, it refers to a device produced through the processes described in this chapter. A micromechanical device is a construct that is mechanical, and not electronic, in nature; it uses gears, mirrors, actuators, and other mechanical systems in their operation. It could be argued that a micromechanical device is a microelectronic device that has at least one moving part. MEMS is a special class, containing a micromechanical device and *integrated* microelectronic control circuitry, thus it is an integrated microelectronic and micromechanical device.

13.39 Why is silicon often used with MEMS and MEMS devices?

See also the answer to Problem 13.2. For MEMS and MEMS devices, silicon is used widely because the manufacturing strategies for silicon have been extensively investigated and developed, and silicon has a unique capability to grow epitaxial layers.

13.40 Explain the purpose of a spacer layer in surface micromachining.

Recall that a spacer layer is a layer of an easy-to-wet etch material. It can separate mechanical devices as they are being built in a layer-by-layer approach, and then removed in a wet etching step that leaves the structural material unchanged. Borophosphosilicate glasses are the most common spacer layer materials.

13.41 What do the terms SIMPLE and SCREAM stand for?

As described in Section 13.14.2 on p. 847, SIMPLE stands for *silicon micromachining by single-step plasma etching* and SCREAM stands for *single-crystal silicon reactive etching and metallization*. These are shown in Figs. 13.39 and 13.40 on p. 848.

13.42 Which process(es) in this chapter allow the fabrication of products from ceramics? (See also Chapter 11.)

By the student. Note that ceramic products are difficult to manufacture on a microscale. The only processes that would work are slip casting from a LIGA-produced mold or equivalent mold from microstereolithography.

13.43 What is HEXSIL?

HEXSIL, shown in Fig. 13.49 on p. 856, combines hexagonal honeycomb structures, silicon micromachining, and thin-film deposition. This process produces high aspect-ratio structures such as the microtweezers shown in Fig. 13.50 on p. 857.

13.44 Describe the differences between stereolithography and microstereolithography.

Microstereolithography uses the same mechanisms as stereolithography, but the laser is focused on a much smaller area. As described in Section 13.16, microstereolithography uses a laser focused onto a diameter as small as 1 μm, whereas conventional stereolithography typically uses laser diameters of 250 μm.

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13.45 Lithography produces projected shapes; consequently, true three-dimensional shapes are more difficult to produce. Which of the processes described in this chapter are best able to produce three-dimensional shapes, such as lenses?

Making three dimensional shapes is very difficult. A shape with a smooth surface is especially challenging, since a stepped surface results from multilayer lithography. Three-dimensional objects can be produced by isotropic etching, but the surface will not necessarily have the desired contour. The best lithography-based process for producing three-dimensional surfaces is stereolithography or microstereolithography, which can be combined with electroforming or other processes, such as LIGA.

13.46 List and explain the advantages and limitations of surface micromachining as compared to bulk micromachining.

By the student. Review Section 13.14.2 and consider the following partial list:

Advantages of surface micromachining:

- Not restricted to single-crystal materials.
- Multilayer objects can be produced.
- Very good dimensional tolerances.
- Complex shapes in multiple layers.
- A mature technology which is fairly robust.

Disadvantages of surface micromachining:

- Additional manufacturing steps are required to deposit and remove spacer layers.
- The process is effectively limited to silicon as the substrate material.
- Wet etchants can result in structures that fail to separate from surfaces, as shown in Fig. 13.36 on p. 845.

13.47 What are the main limitations to the LIGA process?

LIGA has the capability of producing MEMS and micromechanical devices with very large aspect ratios. It also allows the production of polymer MEMS devices and the mass production of these devices (since the LIGA-produced structure is a mold for further processing). The main limitations of LIGA are economic, as collimated x-rays are obtained only with special equipment, currently available only at selected U.S. National Laboratories. Thus, the cost of parts produced is very high.

13.48 Describe the process(es) that can be used to make the microtweezers shown in Fig. 13.49 other than HEXSIL.

The HEXSIL tweezers shown in Fig. 13.49 on p. 856 are difficult, although not impossible, to produce through other processes. The important features to be noted in these tweezers are the high aspect ratios and the presence of lightening holes in the structure, resulting in a compliant and lightweight structure. Although processes such as SCREAM (pp. 855-857) can be used, the required aspect ratio will be difficult to achieve. LIGA also can be used, but it is expensive. For each of these processes, the tweezers shown would require redesign of the microtweezers. For example, in LIGA, it would be desirable to have a draft in the vertical members to aid in molding. However, a structure that serves the same function can be produced, even though vertical sidewalls cannot be produced.

Problems

13.49 A certain wafer manufacturer produces two equal-sized wafers, one containing 500 chips and the other containing 300 chips. After testing, it is observed that 50 chips on each type of wafer are defective. What are the yields of the two wafers? Can any relationship be established between chip size and yield?

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The yield for the 500 chip wafer is (500-50)/500 = 90.0%, and for the 300 chip wafer, it is (300-50)/300 = 83.3%. Thus, given the same number of defects per wafer, the wafer with smaller chips (i.e., more chips per wafer) will have a higher yield. This is because the same amount of defects are spread out over a larger number of chips, thus making the number of defective chips a smaller percentage.

13.50 A chlorine-based polysilicon etch process displays a polysilicon:resist selectivity of 4:1 and a polysilicon:oxide selectivity of 50:1. How much resist and exposed oxide will be consumed in etching 350 nm of polysilicon? What should the polysilicon:oxide selectivity be in order to remove only 4 nm of exposed oxide?

The etch rate of the resist is 1/4 that of polysilicon. Therefore, etching 350 nm of polysilicon will result in (350)(1/4) = 87.5 nm of resist being etched. Similarly, the amount of exposed oxide etched away will be (350)(1/50) = 7 nm. To remove only 4 nm of exposed oxide, the polysilicon:oxide selectivity would be 350/4 = 88:1.

13.51 During a processing sequence, four silicon-dioxide layers are grown by oxidation: 400 nm, 150 nm, 40 nm, and 15 nm. How much of the silicon substrate is consumed?

The total oxide thickness is 400 nm + 150 nm + 40 nm + 15 nm = 605 nm. From Section 13.6, the ratio of oxide to the amount of silicon consumed is 1:0.44. Hence, to grow 605 nm of oxide, approximately (0.44)(605 nm) = 266 nm of silicon will be consumed.

13.52 A certain design rule calls for metal lines to be no less than 2 μm wide. If a 1 μm-thick metal layer is to be wet etched, what is the minimum photoresist width allowed? (Assume that the wet etch is perfectly isotropic.) What would be the minimum photoresist width if a perfectly anisotropic dry-etch process were used?

A perfectly isotropic wet-etch process will etch equally in the vertical and horizontal directions. Therefore, the wet-etch process requires a minimum photoresist width of 2 μm, plus 1 μm per side, to allow for the undercutting, hence a total width of 4 μm. The perfectly anisotropic dry-etch process displays no undercutting and, therefore, requires a photoresist width of only 2 μ.

13.53 Using Fig. 13.18, obtain mathematical expressions for the etch rate as a function of temperature.

The following data points are obtained from Fig. 13.18:

Direction	$1/T$ ($\times 10^{-3} K^{-1}$)	Etch rate (μ/hr)	ln(Etch rate)
⟨110⟩	2.55	70	4.248
	3.3	4	1.386
⟨100⟩	2.55	70	4.248
	3.3	2	0.6931
⟨111⟩	2.55	2	0.6931
	3.3	0.015	-4.200

Figure 13.18 suggests that a plot of ln(Etch rate) vs. $1/T$ will be linear. Therefore, we expect a relationship of the form

$$\ln(y) = a\left(\frac{1}{T}\right) + b$$

or

$$y = e^{a(1/T)+b} = e^b e^{\alpha/T}$$

where y is the etch rate, a is the slope of the $\ln(y)$ vs. $1/T$ curve, and b is the y-intercept. From the data in the table above, we can obtain the following

Direction	a	b
⟨110⟩	-3.816	13.98
⟨100⟩	-4.74	16.33
⟨111⟩	-6.524	17.33

Therefore, the equation in the ⟨110⟩ direction is:

$$y = \left(1.179 \times 10^6\right) e^{-3.816/T}$$

in the ⟨100⟩ direction:

$$y = \left(1.236 \times 10^7\right) e^{-4.74/T}$$

in the ⟨111⟩ direction:

$$y = \left(3.3 \times 10^7\right) e^{-6.524/T}$$

13.54 If a square mask of side length 100 μm is placed on a {100} plane and oriented with a side in the ⟨110⟩ direction, how long will it take to etch a hole 4 μm deep at 80°C using ethylene-diamine/pyrocatechol? Sketch the resulting profile.

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Etching will take place in the $\langle 100 \rangle$ direction, but it should be noted that there will be angled etch fronts at the sides of the square. However, since the width is much larger than the depth, we can ignore these fronts. From Fig. 13.18 on p. 825, the etch rate at 80°C is around 22 μm/hr, so the time required to etch 4 μm is (4/22)(60)=10.91 min.

The resulting profile will look like Fig. 13.23c on p. 831, but the angles of the side walls will be different on the opposite sides of the square.

13.55 Obtain an expression for the width of the trench bottom as a function of time for the mask shown in Fig. 13.17b.

If L is the original trench width and l is the width at the bottom of the trench, then the relationship between l and L is

$$L = l + 2x \tan 54.7^\circ$$

where x is the depth of the trench. The depth of the trench is related to time by the etch rate, or

$$x = ht$$

where h is the etch rate, as given in Tables 13.2 and 13.3 on p. 824 for various etchants and workpiece materials. Therefore,

$$L = l + 2h \tan 54.7^\circ$$

or

$$l = L - 2ht \tan 54.7^\circ = L - 2.824ht$$

13.56 Estimate the time of contact and average force when a fluorine atom strikes a silicon surface with a velocity of 1 mm/s. *Hint:* See Eqs. (9.11) and (9.13).

It should be noted that, at this scale, continuum approaches are no longer valid, and the application of Eqs. (9.11) and (9.13) on p. 553 are useful only for illustrative purposes. However, if we use the properties for silicon ($\rho = 2330$ kg/m^3, $E = 190$ GPa) and we note that fluorine has an atomic radius of 0.119 nm, and an atomic weight of 18.998, so that one atom weighs

$$W = \frac{18.998 \text{g/mole}}{6.023 \times 10^{23} \text{atoms/mole}}$$

or $W = 3.154 \times 10^{-23}$ g/atom. Therefore, the wave speed in silicon is

$$c_o = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{190 \text{ GPa}}{2330 \text{ kg/m}^3}} = 9030 \text{ m/s}$$

The time of contact is, from Eq. (9.11),

$$\begin{aligned} t_o &= \frac{5r}{c_o}\left(\frac{c_o}{v}\right)^{1/5} \\ &= \frac{5\left(0.119 \times 10^{-9}\right)}{9030}\left(\frac{9030}{0.001}\right)^{1/5} \\ &= 1.62 \times 10^{-12} \text{ s} \end{aligned}$$

The contact force is given by Eq. (9.13) as

$$\begin{aligned} F &= \frac{2mv}{t_o} \\ &= \frac{2\left(3.54 \times 10^{-26} \text{ kg}\right)(0.001 \text{ m/s})}{1.62 \times 10^{-12} \text{ s}} \\ &= 4.37 \times 10^{-17} \text{ N} \end{aligned}$$

13.57 Calculate the undercut in etching a 10-μm-deep trench if the anisotropy ratio is (a) 200, (b) 2, and (c) 0.5. Calculate the sidewall slope for these three cases.

For a trench depth is 10 μm, then from Eq. (13.4) on p. 807, we obtain the undercut x as

$$\text{AR} = \frac{E_1}{E_2} = \frac{10 \ \mu\text{m}/t}{x/t} = \frac{10 \ \mu\text{m}}{x}$$

The sidewall slope, θ, is given by

$$\tan\theta = \frac{x}{10 \ \mu\text{m}}$$

The following table can now be constructed:

Anisotropy ratio	Undercut, x, (μm)	Side wall slope, θ (°)
200	0.05	0.28
2	5	26.6
0.5	20	63.4

13.58 Calculate the undercut in etching a 10-μm-deep trench for the wet etchants listed in Table 13.3. What would the undercut be if the mask were made of silicon oxide?

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The same approach as in Problem 13.57 is used. Note that the dry etchants do not have an undercut, but they also etch through silicon dioxide very quickly. While, in theory, a thick mask could be used, in practice it will be difficult to mask a dry etchant with silicon dioxide because the silicon dioxide mask will be removed. The undercut for a perfect mask is:

Etchant	Selectivity	Undercut x (μm)
HF:HNO_3: CH_3COOH	—	10
KOH	100:1	0.1
EDP	35:1	0.28
$N(CH_3)_4OH$	50:1	0.02
SF_6	—	0

If the mask material is silicon dioxide, it will be etched at a rate as given in Table 13.3 on p. 824. While the undercut can be defined based on the original mask dimensions, and therefore yield the same answers as above, we can also calculate the undercut that would be observed in etching a 10m-deep hole. The results are as follows:

Etchant	Etch rate (μm/min)	Time to etch 10 μm trench (min)	SiO_2 removed (nm)	Ref. (nm)	Observed undercut (nm)
HF:HNO_3: CH_3COOH	20	0.5	15	10000	9985
KOH	2	5	50	100	50
EDP	0.75	13.33	2.66	280	277
$N(CH_3)_4OH$	1.5	6.67	0.667	20	19.3
SF_6	0.5	20	0	0	0

13.59 Estimate the time required to etch a spur-gear blank from a 75-mm-thick slug of silicon.

Note that the answer will depend on the etchant used and the ability to replenish the etchant. Using the highest etch rate for silicon in Table 13.2 on p. 823, of 310 nm/min for 126HNO_3:60H_2O:5NH_4F, the time required is

$$t = \frac{75 \text{ mm}}{310 \text{ nm/s}} = 2.42 \times 10^5 \text{ s}$$

or almost three days. This problem demonstrates that etching processes are useful only for thin parts or for shallow (micron-sized) features.

13.60 A resist is applied in a resist spinner spun operating at 2000 rpm, using a polymer resist with viscosity of 0.05 N-s/m. The measured resist thickness is 1.5 μm. What is the expected resist thickness at 6000 rpm? Let α=1.0 in Eq. (13.3).

Equation (13.3) on p. 816 gives the resist thickness as

$$t = \frac{kC^\beta \eta^\gamma}{\omega^\alpha}$$

We can now compare the two conditions and write

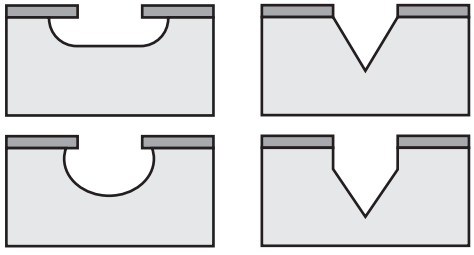
$$\frac{t_1}{t_2} = \frac{k_1 C_1^\beta \eta_1^\gamma \omega_2^\alpha}{k_2 C_2^\beta \eta_2^\gamma \omega_1^\alpha}$$

Note that the only variable which changes is ω. Therefore,

$$\frac{t_1}{t_2} = \frac{k_1 C_1^\beta \eta_1^\gamma \omega_2^\alpha}{k_2 C_2^\beta \eta_2^\gamma \omega_1^\alpha}$$
$$= \frac{\omega_2^\alpha}{\omega_1^\alpha} = \frac{(6000)^{1.0}}{(2000)^{1.0}} = 3$$

Hence, the final thickness will be 1/3 the reference film thickness of 1.5 μm, or 0.5 μm.

13.61 Examine the hole profiles in the accompanying figure and explain how they might be produced.



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It will be helpful to refer to Example 13.2 and Fig. 13.23 on p. 831 to understand this solution below. We can state the following:

- For the top left profile, there is undercut beneath the mask. It is difficult to tell from the dimensions given, but there is either isotropic etching or preferential etching in the horizontal direction compared to the vertical direction. This situation could occur if:
  (a) An isotropic wet etchant is used (see Fig. 13.17a on p. 824).
  (b) The crystal workpiece is aligned so that there is preferential wet etching in the horizontal direction
  (c) An etch-stop has been used.
- The top right figure shows a profile that matches Fig. 13.23d, which is caused by orientation-dependant etching.
- The bottom left figure shows a material that has undercut the mask. Compared to the top right figure, this figure suggests either isotropic etching or etching that is preferential in the thickness direction.
- The bottom right cross section has a vertical wall and a pointed trench. This profile could be produced by a deep reactive ion etching operation or a chemically reactive ion etching operation, followed by an orientation-dependent etching operation.

13.62 A polyimide photoresist requires 100 mJ/cm^2 per μm of thickness in order to develop properly. How long does a 150 μm film need to develop when exposed by a 1000 W/m^2 light source?

It is useful to convert units to avoid confusion in making the calculations. Note that the polyimide photoresist requires the following power density:

$$P = 100\frac{\text{mJ}}{\text{cm}^3(\mu\text{m})t}h = \frac{1000\ \text{Nm}}{t\ \text{m}^2}\frac{h}{(\mu\text{m})}$$

where t is the exposure time and h is the film thickness. Since the power available is 1000 W/m^2, we can calculate the time from

$$1000\frac{\text{W}}{\text{m}^2} = \frac{1000\ \text{Nm}}{t\ \text{m}^2}\frac{h}{(\mu\text{m})}$$

or, solving for t,

$$t = \left(\frac{1000\ \text{Nm}}{1000\ \text{W}}\right)h = 150\ \text{s}$$

13.63 How many levels are required to produce the micromotor shown in Fig. 13.22d?

At a minimum, the following layers are needed:

- Base for rotor.
- Rotor.
- Pin or bearing (it must protrude past the rotor).
- Lip on bearing to retain rotor.

This list assumes that the electrical connections can be made on the same layers as the MEMS features, as otherwise an additional layer is required.

13.64 It is desired to produce a 500μm by 500 μm diaphragm, 25 μm thick, in a silicon wafer 250 μm thick. Given that you will use a wet etching technique with KOH in water and with an etch rate of 1 μm/min, calculate the etching time and the dimensions of the mask opening that you would use on a (100) silicon wafer.

Diaphragms can be produced in a number of ways. This problem and solution merely address the wet etching portion of the process, and assumes a diaphragm can be placed over a proper opening with a diffusion bonding step such as shown in part 3 of Fig. 13.41a on p. 849. Using a wet etchant, a cavity as shown in part 2 of Fig. 13.41a will be produced, with an inclined sidewall. From Table 13.3 on p. 824, note that KOH has a $\{111\}/\{100\}$ selectivity of 100:1. Thus, there will be a slight undercut of the mask, and the sidewalls will have a slope of $\tan^{-1} 0.01 = 0.57°$ from the vertical as shown.

A 25 μm hole needs 25 min at the prescribed etch rate of 1 μ/min. The undercut of the sidewalls will be 0.25 μm at a selectivity of 100:1. Thus, if the top dimensions of the diaphragm are critical, a mask that is 450 $\times$ 450 μm will produce a 500 $\times$ 500 μm dimension. If the *mean* dimension of the diaphragm is critical, then a 475 $\times$ 475 μm mask is needed.

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13.65 If the Reynolds number for water flow through a pipe is 2000, calculate the water velocity if the pipe diameter is (a) 10 mm; (b) 100 μm. Do you expect the flow in MEMS devices to be turbulent or laminar? Explain.

As given by Eq. (5.10) on p. 202, the Reynolds number is

$$\text{Re} = \frac{vD\rho}{\eta}$$

where v is the velocity, D is the channel diameter, ρ is the density of water (1000 kg/m^3), and η is the viscosity of water (8.90×10^{-4} Ns/m^2). Solving for the velocity,

$$v = \frac{(\text{Re})\eta}{D\rho}$$

If the channel diameter is 10 mm, then

$$v = \frac{(2000)(8.9 \times 10^{-4})}{(0.01)(1000)} = 0.178 \text{ m/s}$$

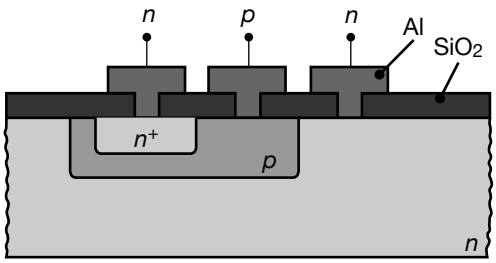
If the diameter is 100 μm, then

$$v = \frac{(2000)(8.9 \times 10^{-4})}{(0.0001)(1000)} = 17.8 \text{ m/s}$$

This is a very high velocity, and probably would never be achieved in a MEMS device. As discussed in Section 5.4.1, laminar flow takes place for Reynolds numbers below 2000. Clearly, MEMS devices will most likely be laminar.

Design

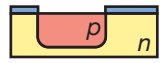
13.66 The accompanying figure shows the cross section of a simple *npn* bipolar transistor. Develop a process flow chart to fabricate this device.



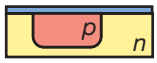
The steps in the production of a simple bipolar transistor are as follows:

1. Oxidation 2. Lithography

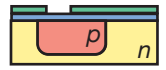
3 Oxide etch 4. Resist removal



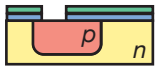
5. *p* region implant



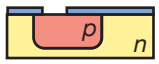
6. Oxidation



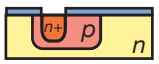
7. Lithography



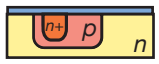
8. Oxide etch



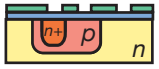
9. Resist removal



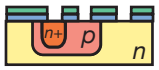
10. n+ region implant



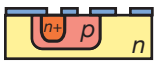
11. Oxidation



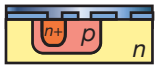
12. Lithography



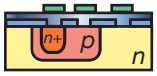
13. Oxide etch



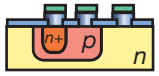
14. Resist removal



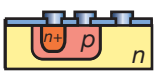
15. Al deposition



16. Lithography



17. Aluminum etch



18. Resist removal

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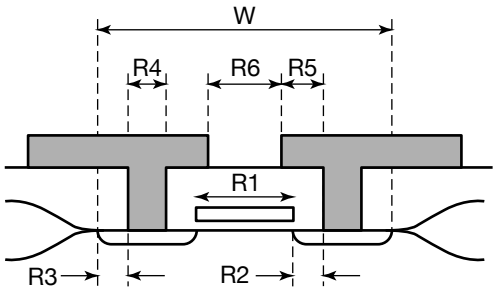
13.67 Referring to the MOS transistor cross section in the accompanying figure and the given table of design rules, what is the smallest transistor size W obtainable? Which design rules, if any, have no impact on the magnitude of W? Explain.



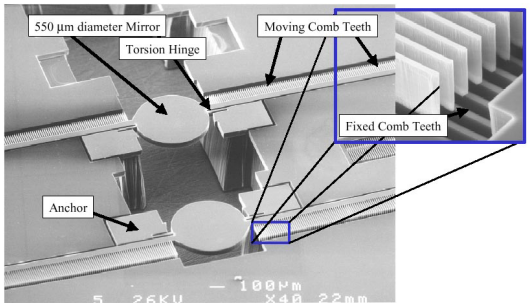
Rule No.	Rule name	Value (μm)
R1	Minimum polysilicon width	0.50
R2	Minimum poly-to-contact spacing	0.15
R3	Minimum enclosure of contact by diffusion	0.10
R4	Minimum contact width	0.60
R5	Minimum enclosure of contact by metal	0.10
R6	Minimum metal-to-metal spacing	0.80

The smallest transistor size, W, that can be obtained using the given design rule is:

$$W = R_3 + R_4 + R_5 + R_6 + R_5 + R_4 + R_3$$

or $W = 0.10 + 0.60 + 0.10 + 0.80 + 0.10 + 0.60 + 0.10 = 2.40$ μm. Design rules R_1 and R_2 have no impact on the smallest obtainable W.

13.68 The accompanying figure shows a mirror that is suspended on a torsional beam; it can be inclined through electrostatic attraction by applying a voltage on either side of the mirror at the bottom of the trench. Make a flow chart of the manufacturing operations required to produce this device.



The device shown in the problem was produced at the University of California at Berkeley Sensor and Actuator Center. As can be noted, the layer below the mirror is very deep and has near-vertical sidewalls; hence, this device was clearly produced through a dry (plasma) etching approach. Also note that it was machined from the top since the sidewall slope is slightly inclined. However, a high-quality mirror could not be produced in this manner. The only means of producing this micromirror is (a) to perform deep reactive ion etching on the lower portion, (a) traditional surface micromachining on the top layer, and (c) then joining the two layers through silicon fusion bonding. (See Fig. 13.48 on p. 856 for further examples of this approach.)

13.69 Referring to Fig. 13.36, design an experiment to find the critical dimensions of an overhanging cantilever that will not stick to the substrate.

By the student. There are several possible solutions and approaches to this problem. An experimental investigation by K. Komvopolous, Department of Mechanical Engineering at the University of California at Berkeley, involves producing a series of cantilevers of different aspect ratios on a wafer. After production through surface micromachining, followed by rinsing, some of the cantilevers attach themselves to the substrate while others remain suspended. The figure below shows the transition. Based on beam theory from the mechanics of solids, a prediction of the adhesive forces can be determined.

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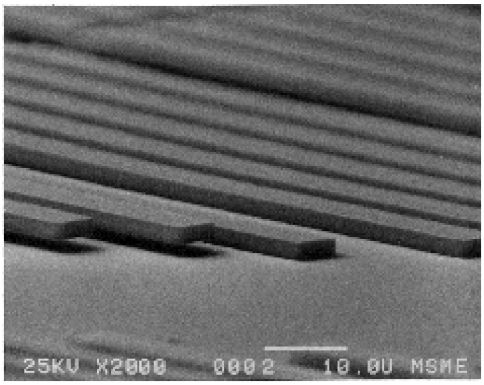

13.70 Explain how you would manufacture the device shown in Fig. 13.32.

By the student. This device would involve a very elaborate series of surface micromachining operations. The solution for Problem 13.66 should be studied and understood before attempting this more complicated problem.

13.71 Inspect various electronic and computer equipment, take them apart as much as you can, and identify components that may have been manufactured by the techniques described in this chapter.

This is a good assignment that can be inexpensively performed, as most schools and individuals have obsolete electronic devices that can be harvested for their components. Some interesting projects also can arise from this experiment. One project, for example, would be to microscopically examine the chips to observe the manufacturers logos, as graphical icons are often imprinted on chip surfaces. See http://www.microscopy.fsu.edu/micro/gallery.html.

13.72 Do any aspects of this chapter's contents and the processes described bear any similarity to the processes described throughout previous chapters in this book? Explain and describe what they are.

By the student. There are, as to be expected, some similarities. For example, the principles of etching processes are the same as in chemical machining (see Section 9.10). Also, there are polishing and grinding applications (as in finishing the wafers and grinding the sides) that are similar to the polishing and grinding processes, described in Chapter 9. Producing silicon wafers involves the Czochralski (CZ) process (see Fig. 5.30 on p. 235). Printed circuit boards are stamped and the holes are drilled, as described in previous chapters. Packaging involves potting and encapsulation of polymers (p. 636). The students are encouraged to comment further.

13.73 Describe your understanding of the important features of clean rooms, and how they are maintained.

Clean rooms are described in Section 13.2. Students are encouraged to search for additional information, such as the design features of HEPA filters, the so-called bunny suits, and humidity controls. It should also be noted that any discussion of clean rooms has to recognize the sources of contaminants (mostly people and their clothing) and the strategies used to control them.

13.74 Describe products that would not exist without the knowledge and techniques described in this chapter. Explain.

By the student. This topic would be a good project. Clearly, a wide variety of modern products could not exist without using the processes described in this chapter. Certainly, the presence of the integrated circuit has had a profound impact on our lives, and any product that contains an integrated circuit would either not exist or it would be more expensive and less reliable. Personal computers, television sets, and cellular phones are other major examples of products that could not exist, or exist in a vastly different form, without integrated circuits are televisions, automobiles, and music players. The students are encouraged to comment further, with numerous examples of their own.

13.75 Review the technical literature and give more details regarding the type and shape of the abrasive wheel used in the wafer-cutting operation shown in Step 2 in Fig. 13.6 on p. 810.

By the student. The main source for such information would be manufacturers and distributors of abrasive wheels. It should be noted

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that the wheel is contoured, hence the wafer does not have a vertical wall. This means that the wafer will have a barrel shape, which is beneficial for avoiding chipping.

13.76 It is well known that microelectronic devices may be subjected to hostile environments (such as high temperature, humidity, and vibration) as well as physical abuse (such as being dropped on a hard surface). Describe your thoughts on how you would go about testing these devices for their endurance under these conditions.

By the student. This is a good topic for students to investigate and develop testing methods for electronic devices. It will be helpful to have students refer to various ASTM standards and other sources to find standardized test procedures, and evaluate if they are sufficient for the difficulties encountered.

13.77 Conduct a literature search and determine the smallest diameter hole that can be produced by (a) drilling; (b) punching; (c) water-jet cutting; (d) laser machining; (e) chemical etching and (f) EDM.

By the student. This is an interesting topic for a web-based research project. Specific dimensions depend on the desired depth of the hole. As examples of solutions for thin foils, there are 10 μm diameter drills available commercially. Laser machining is limited to the focus diameter of the laser, and is usually as small as 1 μm.

13.78 Design an accelerometer similar to the one shown in Fig. 13.32 using the (a) SCREAM process and (b) HEXSIL process, respectively.

By the student. The students should draw upon the manufacturing sequence shown in Fig. 13.54 on p. 862, and consider the capability of the SCREAM and HEXSIL processes to produce large, overhanging structures.

13.79 Conduct a literature search and write a one-page summary of applications in biomems.

By the student. This is an interesting topic for a literature search, and it can be easily expanded into an assignment for a paper. There are many more proposed applications for biomems than realized in commercial products, but sensors used in medicine are widespread, including lab on a chip devices for rapid and simultaneous screening for many conditions. In-vivo applications of MEMS are relatively few in number as of today.

13.80 Describe the crystal structure of silicon. How does it differ from the structure of FCC? What is the atomic packing factor?

This topic is described in Section 13.3. Calculating the atomic packing factor of silicon is complex. It can be shown that the structure is surprisingly very open, with a packing density of 34% as compared to 74% for fcc crystals.

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